



Wind Atlas for South Africa (WASA) – Best practice guide for application of WASA

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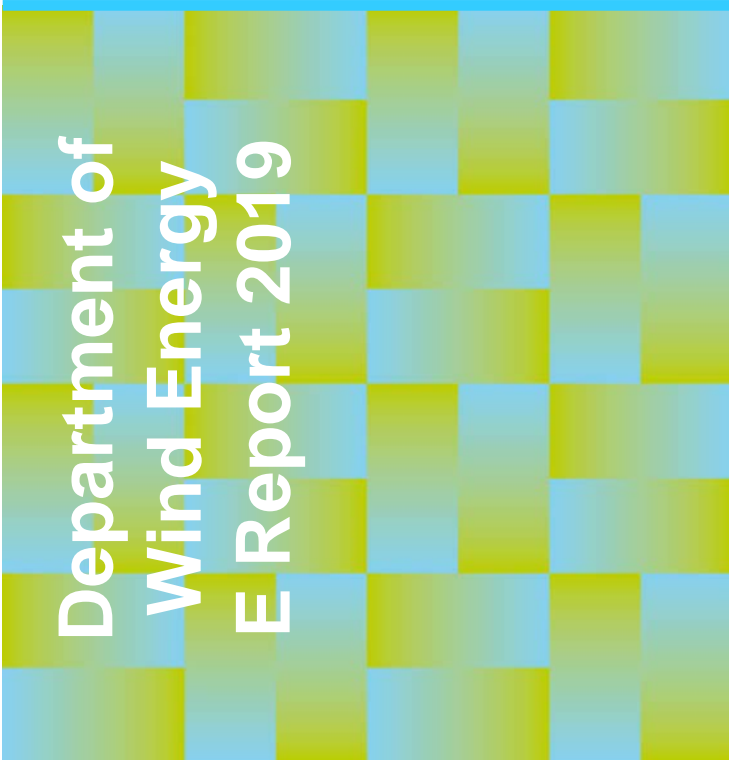
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Wind Atlas for South Africa (WASA) – Best practice guide for application of WASA



Department of Wind Energy E Report 2019

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Title: Wind Atlas for South Africa (WASA) –
Best practice guide for application of WASA

Summary (max 2000 characters):

The present report is a best practice guide for application of results from the Wind Atlas for South Africa (WASA). A general description of the methodological framework – the wind atlas methodology – is given, including validation results of the numerical wind atlas at 15 measurement sites. The atlas can be applied for different purposes – from siting of wind turbines to planning of wind farms – and the requirements and considerations for this are outlined. Furthermore, a number of case studies are described, which illustrate different applications and may serve as a guideline and inspiration for new wind energy projects. The report also contains detailed instructions for accessing and using the WASA data.

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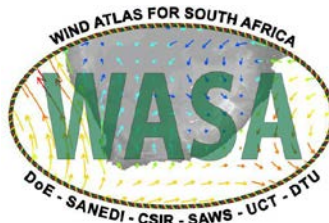
Wind Atlas for South Africa (WASA)

Phase 1 and Phase 2

Best practice guide for application of WASA

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December 2018

Best practice guide for application of WASA

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1 Introduction

1.1 WP 4 of the WASA Project

Work Package 4 (WP04 and WP24) entitled “Application” is a part of the Wind Atlas for South Africa (WASA) project.

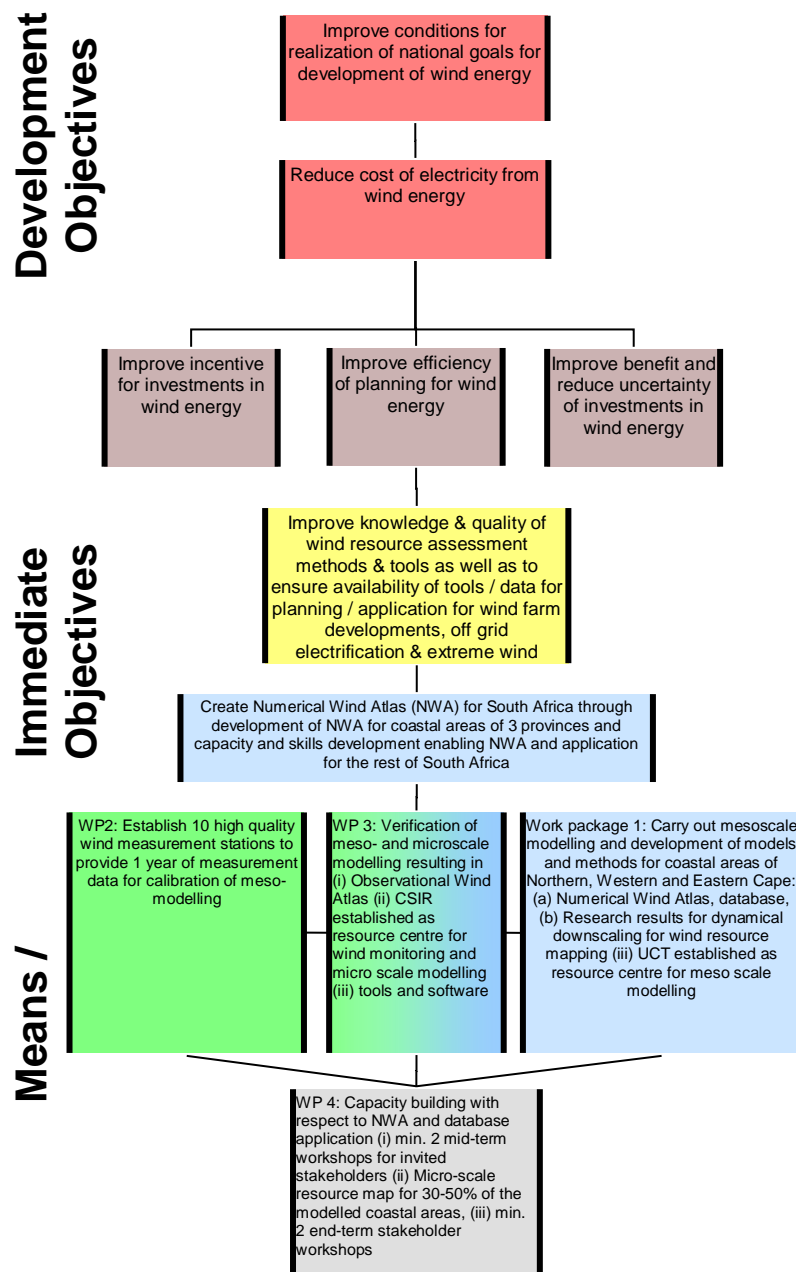


Figure 1. Objective tree of the WASA project as described by the Project Document¹.

In view of the objectives of the WASA project as shown in Figure 1, the project should build expertise in mesoscale modelling, microscale modelling with WAsP, as well as in measurement techniques, data analysis and preparation of wind atlases. This has all been achieved through WPs 01, 02, 03, 04 and

¹ Since the formulation of the Project Document, the WASA project team has decided to use the term “validation” for the WASA context instead of “verification”, which was generally used previously and in the Project Document.

05. The use of results for actual applications has been referred to work package WP 4, in order to provide a particular focus on this aspect for relevant parties other than the project partners developing the wind atlas – SANEDI, UCT, CSIR, SAWS and DTU.

This report seeks to collect the necessary information and instructions for any interested party to be able to apply the results of the “Wind Atlas for South Africa (WASA)” project. The report will briefly describe

- The Wind Atlas Method – some history and how it has been used by the project to generate the
 - Numerical Wind Atlas (WRF based)
 - Observational Wind Atlases at the WASA masts WM01-WM15
 - High-Resolution Wind Resource Map
 - Extreme Wind Atlas
- The application opportunities – who would be able to use the Numerical Wind Atlas and for what
- How to apply the Numerical Wind Atlas for wind energy planning or wind farm project development by employing the Wind Atlas Method and WAsP.
- Case studies to illustrate possible ways of applying the Numerical Wind Atlas
- Summing-up best practices and brief guidance

2 Wind atlas methodology

2.1 Introduction

The wind atlas methodology was developed in the 1980's and used initially for the creation of the European Wind Atlas. The wind resource assessment for the EWA highlighted the need for a microscale flow model and consequently the Wind Atlas Analysis and Application Program (WAsP) was conceived and developed at DTU Wind Energy (then Risø National Laboratory). WAsP made what we now call an observational wind atlas as described below. During the 1990's, techniques to employ mesoscale models were developed, which made it possible to model larger domains, mesoscale effects, and long-term wind climates. Recently, techniques have been combined for the development of wind atlases in countries with scarce measurement stations, and systematic validation against known values has proven effective. This section of the application report briefly describes the updated state-of-the-art wind atlas methodology as it is used in the WASA project. Figure 2 illustrates the elements in tabular form, showing the interfaces and processes of:

- Microscale modelling leading to the Observational Wind Atlas
- Mesoscale modelling leading to the Numerical Wind Atlas
- Measurements as inputs to the Observational Wind Atlas and to Validation
- Validation comparing the Observational and Numerical Wind Atlases at measurement locations
- Application of results leading to wind climate and power production estimates

Mesoscale	Pre-processing Wind classes Terrain elevation Terrain roughness Input specifications Model setup	Modelling KAMM WRF MC2 MM5 etc.	Post-processing Predicted wind climate Regional wind climate Predicted wind resource for selected terrain site coordinates	Numerical WA Mesoscale maps Database WAsP *.LIB files Uncertainties Parameters
Measurements	Met. stations Siting Design Construction Installation Operation	Wind data Data collection Quality control Wind database Wind statistics Observed wind climate	Verification Meso - and microscale results vs. measured data Adjust model and model parameters to fit data Satellite imagery (offshore sites only)	Applications Best practices Courses and training Microscale flow model Wind farm wake model ⇒ Wind farm AEP
Microscale	Pre-processing Wind speed distributions Wind direction distribution Terrain elevation Terrain roughness Sheltering obstacles	Modelling WAsP MS-Micro CFD-models etc.	Post-processing Regional wind climate Predicted wind climate Predicted wind resource for selected terrain site coordinates	Observational WA Microscale maps Database WAsP *.LIB files Uncertainties Parameters

Figure 2. Wind atlas methodologies use wind measurements, as well as microscale and mesoscale modelling for wind resource assessment and siting (Hansen et al., 2007).

2.2 Microscale observational wind atlas

As the name implies, an *observational wind atlas* is based on observed wind climates from a dense network of meteorological stations or, alternatively, it is a wind atlas with a geographical validity limited to the immediate surroundings of the mast (or masts) from which the observations for the wind atlas were made. The latter is the case in the WASA Phase 1 and Phase 2 project, using 15 masts for the

validation of the mesoscale modelling (the Numerical Wind Atlas) that at the same time provide data for 15 discrete Observational Wind Atlas data sets.

The observed wind climates contain the wind speed and direction distributions derived from long-term time-series of wind speed and direction measurements at the meteorological stations. The observed wind climates are thus representative for specific locations and heights above ground level; so, in order to be able to predict the wind climate at a given wind turbine or wind farm site, the observed wind climates must be transformed into *generalised wind climates*. This may be done using the wind atlas methodology of the European Wind Atlas, see Figure 3.

Employing detailed descriptions of terrain elevation, land cover and occurrence of sheltering obstacles around each meteorological station, the observed wind climate is transformed into what would have been measured at the location of the station if the surroundings were completely flat, featureless and with a homogeneous surface, and the measurements had been taken at, say, 10, 25, 50, 100 and 200 m a.g.l. Through this transformation procedure, the observed wind climate is freed from the influence of local topography to become *generalised* or *regionally representative*.

This results in an observational wind atlas, given in the form of detailed statistics of the generalized wind speed and direction distributions for the locations of the meteorological stations. These data sets can then be used as inputs to the application process, whereby the same models are used in reverse to transform the generalised wind climate to the *predicted wind climate* at any specific site and height near the station.

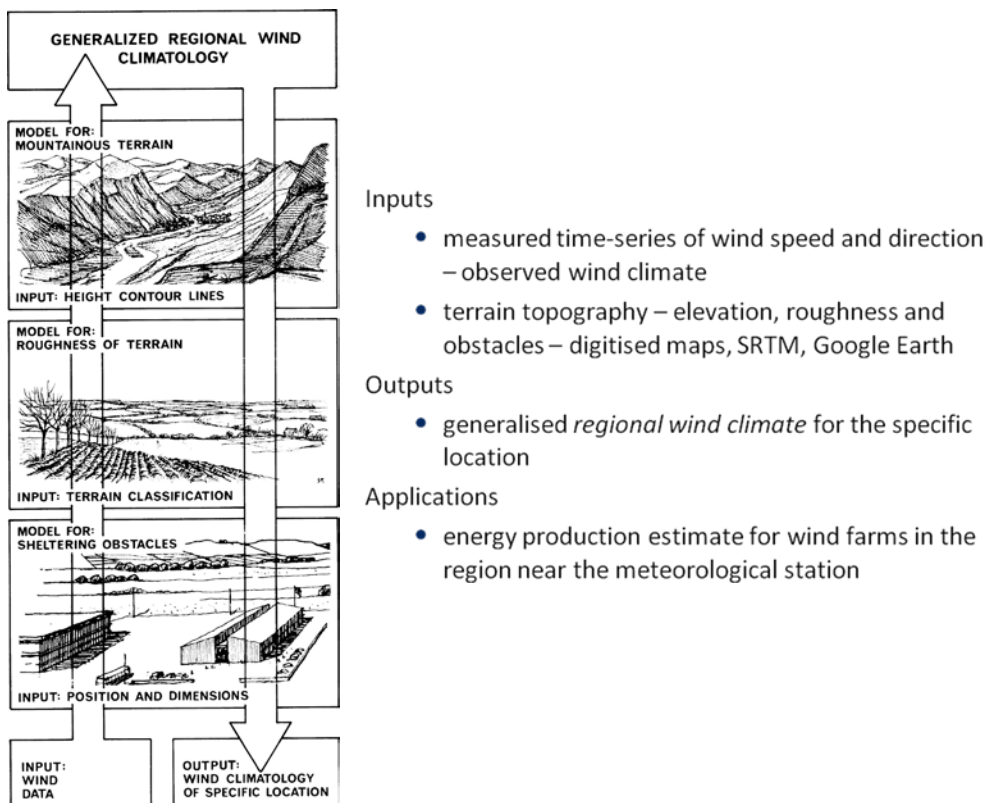


Figure 3. The wind atlas methodology will generate the Observational Wind Atlas (generalised wind climate) for the location of the mast providing the wind data (observed wind climate).

2.3 Mesoscale numerical wind atlas

Numerical wind atlas methodologies have been devised to solve the issue of insufficient wind measurements, which render wind resource mapping efforts through observational methodologies problematic. A so-called *downscaling* approach is applied, connecting the large-scale long-term global data sets via mesoscale modelling to the smaller-scale local wind climates in a given area.

The output from long-term simulations using a mesoscale model is now widely used to generate the wind climatology necessary for calculating the wind energy resources of a given geographical area (Hahmann et al., 2015c). These wind climatologies are useful when validated against measurements and serve as input to microscale models for further downscaling (Badger et al., 2014). In this project such a method has been applied.

The Numerical Wind Atlas method was developed at DTU applying an adapted approach to statistical-dynamical downscaling (Frey-Buness, F., D. Heimann, R. Sausen, 1995.). The basis for the method is the existence of a robust relationship between meteorological situations at the large-scale and meteorological situations at the small-scale. Information about the large-scale atmospheric forcing is freely available from different reanalysis data-sets, e.g. as the ECMWF, 2016, ERA5 applied here for the 2018 WASA Phase 1 and Phase 2 analyses. Figure 4 shows a schematic diagram illustrating how the mesoscale modelling results are combined to give regional wind climates in the numerical wind atlas system. The simulations used to generate the WASA numerical wind atlas utilise the Advanced Research WRF (ARW-WRF) version 3.8.1 model released on August 12, 2016. The WRF modelling system is in the public domain and is freely available for community use. The mesoscale model, WRF, is used to create a wind time series and statistics representing the climate of the region. The results are combined to create the mesoscale wind resource. The mesoscale wind resource can be transformed to regional *generalised wind climates*, thus arriving at a numerical wind atlas (e.g. with 3 or 5 km resolution), similar to the observational wind atlas (where observations exist).

Both these methods are described in great detail in the dedicated reports regarding the mesoscale modelling part of the project.

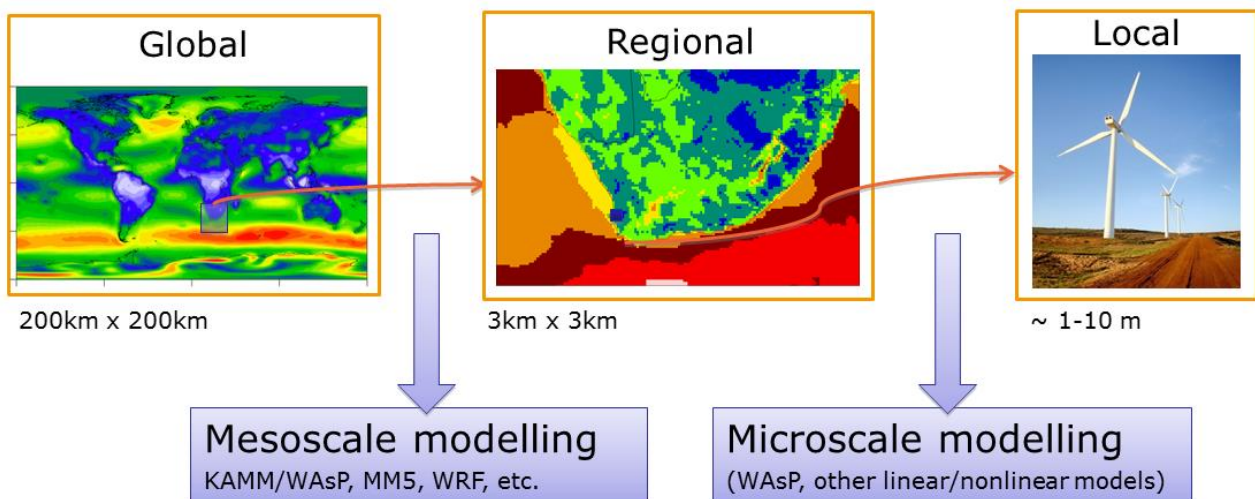


Figure 4: Schematic showing the numerical wind atlas methodology.

WM 09	25.028380	31.252540	1806	312,258	6,540,734	35J
WM 10	28.135950	32.090650	925	607,194	6,448,952	35H
WM 11	28.07351	30.81436	2575	602,685	6,590,479	35J
WM 12	30.52871	29.85026	770	261,255	6,695,243	36J
WM 13	32.16636	27.42605	80	417,602	6,966,098	36J
WM 14	29.54348	27.88169	2045	750,400	6,913,303	35J
WM 15	27.12303	28.62023	1505	512,026	6,834,082	35J

2.4.2 Layout of wind measurement masts and instrument overview

The fifteen 60-m masts, WM01-WM15, instrumented with DTU-developed anemometers, have been the focus of the measurement programme and of the validation. This type of instrumentation has been used for studies worldwide and for obtaining high-quality data. The measurement equipment is described in detail in the dedicated Measurement Report. The instrumentation at each height level is briefly listed in Table 2 and the layout is shown schematically in Figure 7.

Table 2. List of measured properties and instruments used at each measurement station.

Measured property	Instrument	Nominal height [m a.g.l.]
Wind speed	WindSensor P2546A cup anemometer	10, 20, 40, 60, 62
Wind direction	Vector Instruments W200P wind vane	20, 60
Absolute temperature	Vaisala HMP45A humidity and temperature probe	60
Temperature gradient	Risø DTU P2642A Pt 500 resistor	60 to 10
Barometric pressure	Vaisala PTB110 barometer	6
Relative humidity	Vaisala HMP45A humidity and temperature probe	60

Data loggers/ CompactFlash Module

Model: CR1000 / CFM100

Manufacturer: Campbell Scientific, Inc., United Kingdom

Height: 6 m

Calibrated by: Campbell Scientific Ltd, United Kingdom

Data Capturing

Data are sampled with a frequency of 0.5 Hz. Every 10 minutes, statistics of the measurements – average, minimum, maximum, standard deviation – are calculated and recorded together with date and time information.

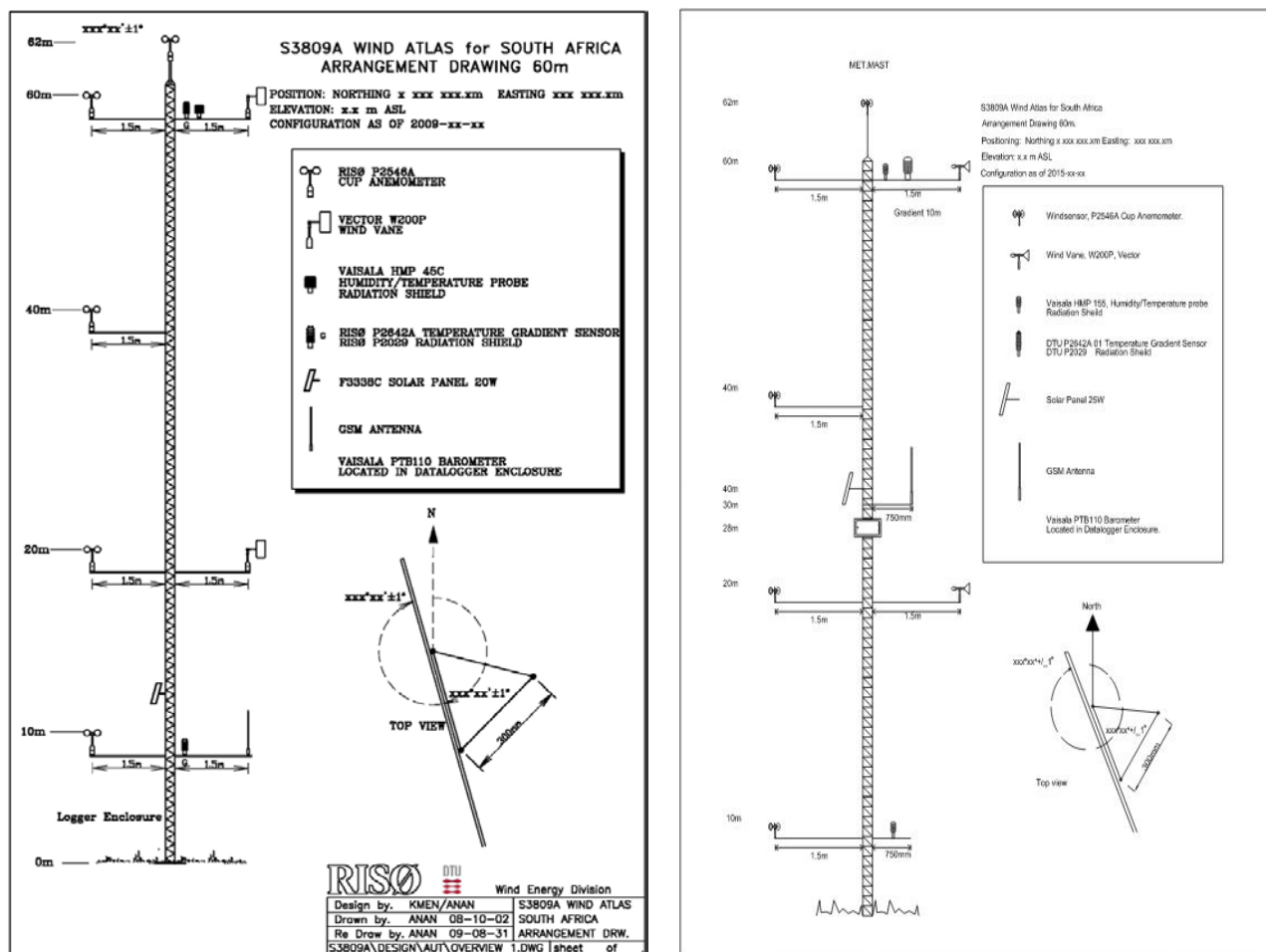


Figure 7: Drawing of mast layout and sensor equipment: to the left WASA1 (WM01-WM10) and to the right WASA2 (WM11-WM15) masts. WASA1 and WASA2 stations are almost identical with just small structural differences in the masts – for details see site description and measurement reports.

2.4.3 Availability of wind measurements

Table 3 shows the status of the meteorological measurements at the time of writing.

Table 3. Status of measurements: The **Recovery** column shows the overall data recovery rate for the top-level anemometer/wind vane only; and the **Years** column show the available measurement period.

Mast ID	Province	Data start Date	Data start Time	Period [y]	Recovery [%]
WM01	NC	2010-06-23	20:20	7	99.9
WM02	NC	2010-06-30	13:10	8	97.5
WM03	WC	2010-06-24	15:40	8	100.0
WM04*	WC	2010-05-18	18:00	3	100.0
WM05	WC	2010-05-20	16:50	8	92.5
WM06	NC	2010-09-17	15:10	7	99.9
WM07	WC	2010-05-28	16:20	8	98.9
WM08	EC	2010-08-04	13:00	8	95.3

WM09	NC	2010-09-01	14:30	7	92.6
WM10	EC	2010-08-05	14:00	7	99.0
WM11	EC	2015-10-27	15:00	2	97.2
WM12	NL	2015-10-28	12:00	3	99.5
WM13	NL	2015-10-15	11:30	3	100.0
WM14	FS	2015-10-02	15:50	3	100.0
WM15	FS	2015-10-13	08:50	3	97.2

* WM04: until 6 June 2013, where the station ceased operation.

2.4.4 Meteorological data download

Meteorological data from the 15 measurement stations can be downloaded from the web site: wasadata.csir.co.za/wasa1/WASADData. Download is free of charge, but requires registration.

The WASA data download site also contains links to the WASA Wind Atlas download site, which contains results from the micro- and mesoscale modelling, as well as further information, reports and tools.

3 Validation of the Numerical Wind Atlas

The value of a wind atlas depends on the uncertainty of the estimates made when applying it. It may vary for various applications, like wind resource assessment, energy production estimates of a wind farm or design wind conditions or other uses. In any case, a thorough validation employing high-quality measurements is essential for quantification of uncertainties. This may be achieved by comparison of wind speed and direction distributions derived from both numerical wind atlases and measurements. By comparing wind climates based on modelling to those based on measurements for several wind measurement stations, an assessment of the uncertainty of the modelling-based estimate can be made.

Often the validation of a mesoscale-derived wind resource assessment is made by simply comparing the predicted average wind speed to a measured mean wind speed at the mast site. However, ideally modelling and measurements should be compared and validated for many climate statistics at many heights, and for many timescales in all types of terrain and climates in the model domain. Such a validation effort would be very time-consuming and the validation effort is therefore a balance between effort and value that it creates as illustrated in Figure 8.

The WASA project has been designed to make a significant effort regarding validation, made possible by the network of high-quality measurement stations spaced across the country in carefully selected locations. It is attempting in the various Work Packages to provide a broad selection of statistical comparisons applying appropriate knowledge of the measurements as well as the meso- and microscale modelling techniques. This section is trying to extract an overview of these efforts.

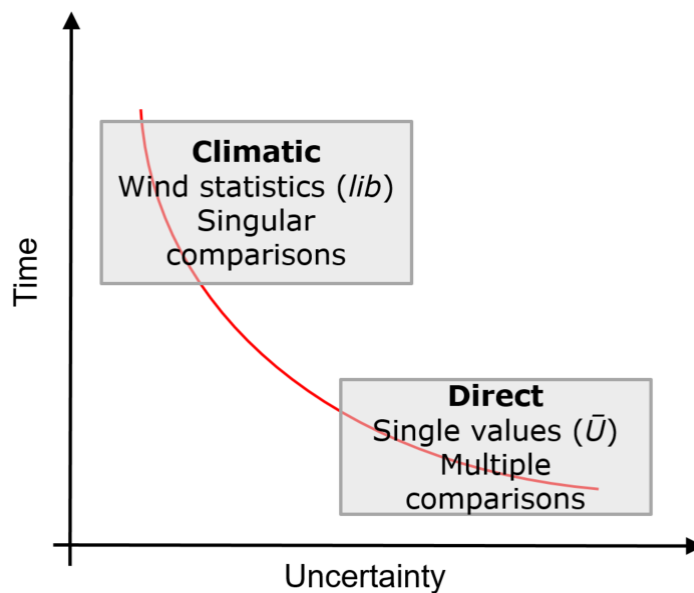


Figure 8: Validation of a Numerical Wind Atlas needs to go beyond direct comparison of single values based on mesoscale model simulations to available measured single values – which requires long-term measurements and modelling as well as a significant effort.

The process of validation aims to evaluate the uncertainty of an estimate of wind resource, whether based on the observational wind atlas or the mesoscale numerical wind atlas methodologies. Central to the validation process is the principle that a proper comparison of wind characteristics is being made. As examples: just as it makes little sense to compare a mean wind measured at 25 m a.g.l. with a mean wind measured at 80 m a.g.l., even at the same location, *without* accounting for a vertical wind profile, it makes little sense to compare a mean wind measured at a lakeside with a mean wind measured in a semi-urban area, *without* accounting for the effect of surface roughness. Similarly, for measurements

made on top of a hill, the orographic speed-up effect must be accounted for. Accounting for these kinds of effects is the backbone of the wind atlas methodology and the models within the WASP software. This principle *must* also be used when comparing mesoscale modelling results to measurements, because the spatial representation of the terrain in the model is impacted by the spatial resolution, even at high resolutions. Roughness conditions varying on a scale smaller than the grid scale will not be represented. Sharp or steep surface elevation features will tend to be smoothed and rounded by the grid scale representation. Therefore, the wind climate given by a particular grid cell of a model cannot be directly compared to a measured wind in the vicinity of the same grid cell. The necessary step is to transform the mesoscale model winds to standard conditions to account for the effects of the roughness and orography as represented in the mesoscale model to provide the winds for generalised mean flat terrain with a single homogenous surface roughness.

A number of high quality and well distributed wind measurement stations are needed to validate the model output and, as described above, these have been established in the South African geographical area for the “Wind Atlas South Africa” project. A chain of carefully executed and well documented activities are needed to provide these locally measured data. The same careful approach is needed regarding the use and interpretation of externally measured wind data.

For locations where there are measurements, validation is possible at these locations. However, the relatively large spatial coverage of the WASA domain means that validation is a challenge as the number of data points in relation to the number of wind measurement stations is relatively large. We address this issue by considering validation in a variety of ways.

For the location, there are multiple ways that a validation can be performed and presented, which try to cover a range of different kinds of comparison. For example, it is possible to compare the generalized wind climate derived from measurements with that derived from the mesoscale simulations. It is also possible to downscale the generalized wind climate derived from the mesoscale simulations to give the predicted wind climate at the measurement site, and compare this with the measured wind climate.

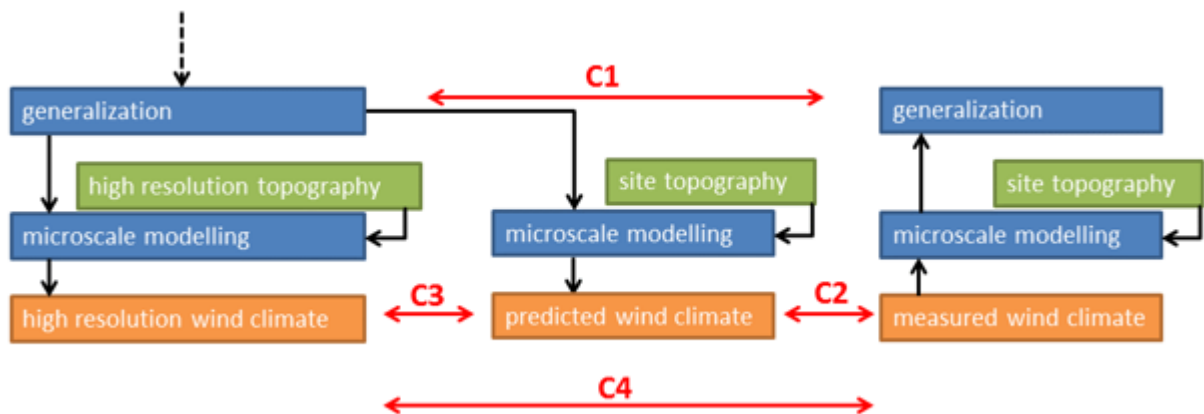


Figure 9: Schematic showing how validation can be performed by number of different comparisons, indicated by C1 through C4. **C1** is the comparison of generalized wind climates derived from mesoscale modelling with the generalized wind climate derived from wind measurements. **C2** is the comparison of the downscaled climate based on the generalized wind climate derived from mesoscale modelling with the measured wind climate. **C3** is the comparison of the wind climate at the nearest calculation node of the WASA with the predicted wind climate downscaled based on the generalized wind climate derived from mesoscale modelling. **C4** is the comparison of the wind climate at the nearest calculation node of the WASA with the measured wind climate.

Comparison of predicted wind climate at the site with the nearest calculation node from the WASA is also possible. This comparison shows the uncertainty introduced by approximating the site position and the uncertainty introduced by using the global high resolution topography datasets instead of the site topography. It is also possible to compare the measured wind climate with the nearest calculation node from the WASA. This comparison shows the uncertainties from generalized wind climate, description of the topography and flow modelling and approximation of the location all together.

The procedure for the validation of WASA is illustrated in Figure 9. The two blue arrows indicate the comparisons at the GWC level and the PWC level.

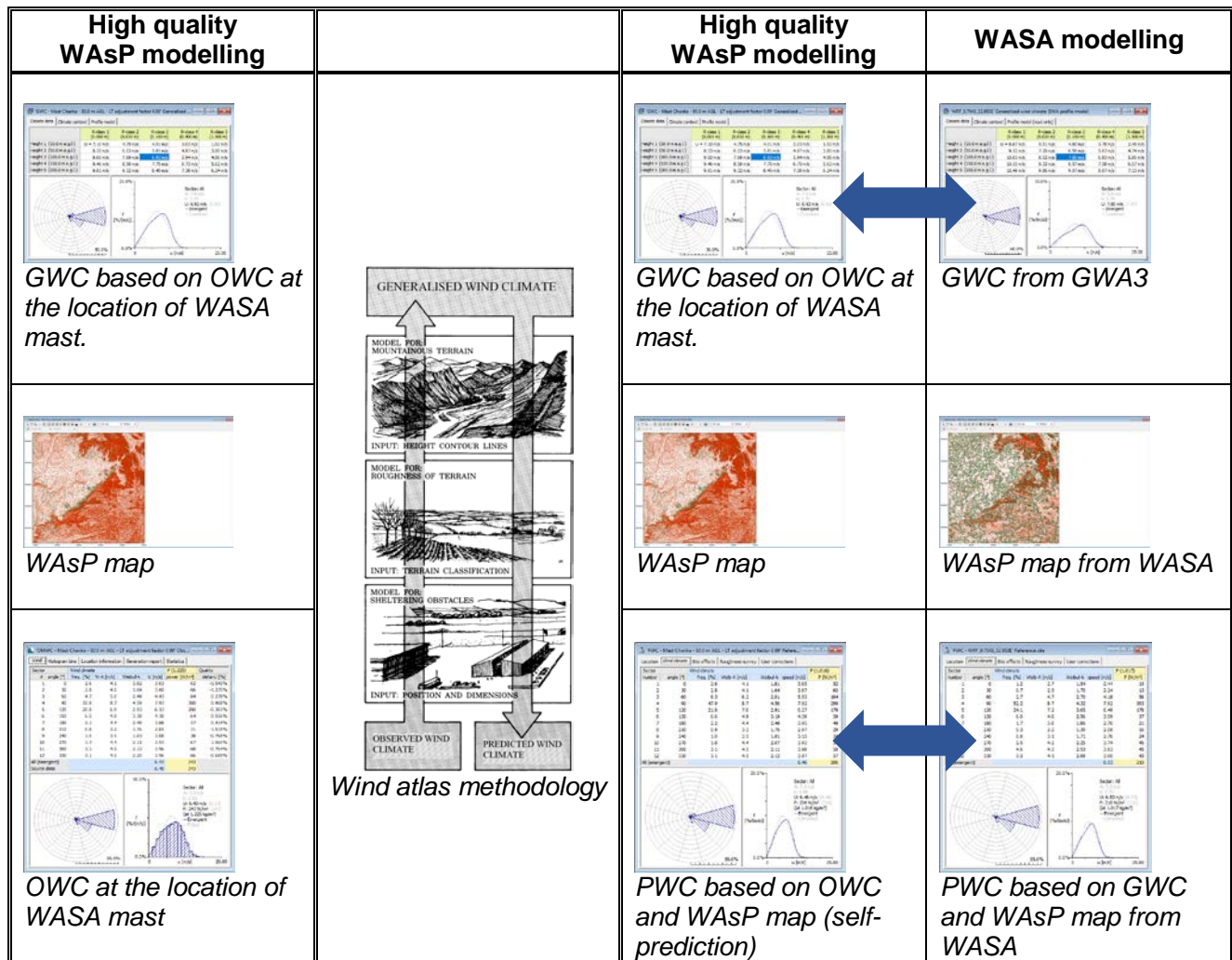


Figure 10: The procedure for the validation of WASA. The two blue arrows indicate the two comparisons at the GWC level (top right) and the PWC level (bottom right)

Overall the qualitative agreement of the modelling and measured results is good, as seen from this validation. The mesoscale modelling in terms of agreement of mean wind speed gives a performance that is comparable to – and even better than – that found in other studies.

The validation is carried out at the 15 WASA masts, where the Numerical Wind Atlas (NWA) is compared to observational wind atlas (OWA). Generalized annual mean wind speed [m/s] at 100 m, $z_0 = 3$ cm of the NWA are compared to the OWA. Validations have been carried out in the 2014 version of this Best practice guide for application of WASA report for both the first KAMM-based NWA (launched March 2012) and the researched WRF-based NWA that was released April 2014 – available on the www.wasa.csir.co.za. This December 2018 updated version of the Best practice guide for application of

WASA report deals with the validation of the updated WRF-based NWA December 2018 versus the expanded WASA measurement programme now for the extended period and the masts WM01-WM15.

3.1 Main findings at the generalised wind climate level

Table 4: Summary of generalised wind climate at height 100.0 m a.g.l. and roughness class 0.100 m for 15 sites in South Africa.

Site	Mean wind speed	
	WAsP modelling	WRF modelling
	[m/s]	[m/s]
WM01	6.62	5.69
WM02	6.57	6.61
WM03	7.23	6.53
WM04	7.46	7.21
WM05	8.60	8.00
WM06	7.73	7.68
WM07	7.35	6.99
WM08	7.77	7.64
WM09	7.71	7.87
WM10	6.93	6.91
WM11	6.53	7.28
WM12	5.46	5.25
WM13	6.20	6.25
WM14	7.12	7.46
WM15	6.06	6.13

3.2 Main findings at the predicted wind climate level

Table 5: Summary of predicted wind climates at height 62 m a.g.l. for 15 sites in South Africa.

Site	Mean wind speed		Mean power density	
	Observed wind speed	Modelled wind speed	Observed power density	Modelled power density
	[m/s]	[m/s]	[W/m ²] / [GWh]	[W/m ²] / [GWh]
WM01	6.04	5.20	305 / 5.0	189 / 3.6
WM02	6.17	6.13	240 / 4.7	273 / 4.7
WM03	7.14	6.32	365 / 6.8	292 / 5.3
WM04	6.66	6.32	321 / 6.1	286 / 5.6
WM05	8.45	7.88	613 / 8.7	530 / 7.8
WM06	7.34	7.21	365 / 6.3	402 / 6.3
WM07	7.07	6.49	326 / 6.1	302 / 5.3
WM08	7.27	6.98	422 / 6.8	420 / 6.4
WM09	7.82	7.75	410 / 7.0	492 / 6.9
WM10	6.66	6.43	302 / 5.4	301 / 5.1
WM11	7.51	8.25	417 / 6.1	651 / 6.9
WM12	5.07	4.89	141 / 2.9	161 / 2.9
WM13	5.10	5.08	156 / 3.3	160 / 3.4
WM14	7.36	7.68	355 / 6.1	465 / 6.7
WM15	6.09	6.16	201 / 4.4	270 / 4.8

Any user or application can establish their own mast and perform validation at any other point in South Africa and thereby confirm and quantify the usefulness and uncertainty levels associated with the application of the Numerical Wind Atlas in South Africa.

3.3 Some general aspects of uncertainties and sensitivities in wind resource assessment and production estimation

Wind resource assessment is known to be associated with numerous types of uncertainties, many of which have been discussed in the literature for many years, see e.g. “Accuracy of Estimation of Energy Production from Wind Power Plants”, Wind Engineering, Vol. 16 No. 5, 1992. This section contains some general comments on some of the main classical types of uncertainties that always have to be considered in wind resource assessment.

3.3.1 Uncertainties related to long-term and regional variations in wind climate

Any wind resource assessment exercise should attempt to make the necessary adjustment of the measurement period relative to the long-term average wind climate, i.e. the variability of the wind climate, longer-term variations and climatic change.

Most of the WASA stations have recorded the wind climate for just three to eight years and may therefore not be able to provide the full necessary information. However, there are SAWS station data available that have measured wind for long periods, although not necessarily with dedicated wind instrumentation or siting for wind energy purposes. Corrections when using such data should be applied following a careful investigation of the history of the station.

Long-term wind data series are also available from various re-analyses data sets such as the ERA, NCEP/NCAR and other reanalysis data sets, but it is not yet fully clear how well these data can be used to estimate the long-term variations close to the ground in South Africa.

Little is known about climatic changes in this region and the impact these may have on the energy production from wind farms in the very long term – and it was not part of the project to investigate this aspect in depth.

3.3.2 Large-scale effects on wind climate by large wind farms

It should be mentioned that large wind farms will potentially affect the wind climate – at least in the near surroundings – and therefore affect the production of neighbouring wind farms. The uncertainty due to such large-scale effects on wind climate by large wind farms is difficult to quantify and it is currently a subject for research. However, results of this research will be relevant for large-scale land based applications in South Africa as well.

3.3.3 Gradients in wind climates

It can be seen from the mesoscale modelling results and the Numerical Wind Atlas that spatial gradients in the wind climate can be significant.

The technique for interpolation between wind atlases may be considered. For sites with a large spatial extent, ‘interpolation’ using the WRF-based NWA results presented should be used. However, these results are not sufficiently accurate for obtaining bankable wind resource estimates for wind farm design optimization. On-site measurements must be carried out in order to increase the accuracy of the results. The NWA will be useful to design such a measurement programme – both in terms of the number of measurement masts necessary and their location.

3.3.4 Uncertainties related to flow modelling – WAsP and WRF

The uncertainties associated with WAsP flow modelling in general have been described by the Microscale Report and in the manual for WAsP. Most of these uncertainties are well known and will also apply to South Africa. Most of these uncertainties are not particularly pronounced in large parts of South Africa, with relatively flat and gently undulating terrain, and their sum will generally be relatively small when adhering to good engineering practices. However, micro-scale modelling in complex terrain with steep slopes is associated with potentially large uncertainties.

One point that deserves more attention in the future, though, is the extrapolation of wind climate estimates to greater heights (100-250 m above ground level) from measurements made at heights of 50-100 m a.g.l.

More details are available in the WASA Mesoscale Report.

3.3.5 Uncertainties related to wind measurements

This type of uncertainty can be significant and it is mainly related to the instruments used, as well as their calibrations and mounting on the masts, including e.g. the lengths and orientations of the mounting booms.

The WindSensor P2546A cup anemometer was used as standard for all the measurement levels on all the 15 measurement masts. Instrumentation was designed, implemented and checked as reported in the Site Description Report and the Measurement Report. All the data have been quality controlled in the WASA team in accordance with good measurement practice. Measurement uncertainty can be estimated from a traditional analysis based on the guidelines in the IEC standard.

3.3.6 Uncertainties related to topographic data

Topographic data can be significant source of uncertainty – e.g. regarding

- accuracy and sufficiency of terrain description
- use of coordinate systems, projections, datums
- interpretation of land cover types and roughness length
- major developments and their representation in maps

The sensitivity of wind resource assessment with regard to the accuracy and detail of the topographical input data were studied in WASA.

3.3.7 Uncertainties of wind turbine and wind farm power performance

The uncertainty of the wind turbine power performance has not been studied in this project. However, some parameters have been considered, including e.g. air density and the vertical profile.

4 Application of the wind atlases

4.1 Typical users and uses of the atlas

In very general terms, the typical use of a wind atlas may be categorised as listed in Table 6 below. As shown, there is a very wide range of possible applications and therefore a corresponding range of needs and expectations when it comes to the form and even accuracy of the result.

Table 6. Typical users and uses of a wind atlas.

Policy makers	Policies and regulations
Planners	Resource and development planning
Investors, owners and banks	Financial planning, risk assessment and decisions
Developers (small and large)	Project development for wind farms and turbines
Industry (small and large)	Project design and implementation, Wind turbine design and development
Power sector	Power system planning, development and operation
Consultants	Independent expertise and tools development
Academic community	Research, tools development & education

4.2 Applications of the numerical wind atlas

The use of a numerical wind atlas is typically either related to policy making, planning or project development, each with a number of possible subtasks, like

- **Policy making**
National, provincial and local – energy, economy and sustainability policy making
- **Planning**
National, provincial and local – physical, resource and power system planning
- **Project development**
Wind farm siting and layout – energy production estimation, site assessment, wind turbine design conditions

Useful inputs to these main types of wind-related tasks may be achieved through applying the wind atlas databases to one or more of these types of analyses.

1	Wind resource assessment and predicted wind climates for a site, an area, or a region
2	Wind energy planning databases and graphics
3	Wind farm Annual Energy Production (AEP) estimations
4	Wind turbine design conditions, e.g. as specified in IEC 61400-1

This may all be achieved by using the Wind Atlas databases, i.e. by transformation of the Generalised Wind Climate (wind atlas *.LIB or *.GWC files) to the Predicted Wind Climate (PWC), i.e. the predicted near-surface wind speed and direction distributions, using WAsP or a similar micro-scale model.

4.3 Wind-climatological inputs

The wind-climatological inputs are described in detail in other WASA reports. Generalised wind climate data sets derived from the mesoscale modelling are described by Hahmann et al. (2014) and Hahmann et al. (2018) and data sets derived from the measurements by Mortensen et al. (2014), Mortensen et al. (2018) and Stander et al. (2018). Figure 11 shows examples of these generalised wind climates. Note that the heights have been adapted to the measurement heights in the observation-based data set.

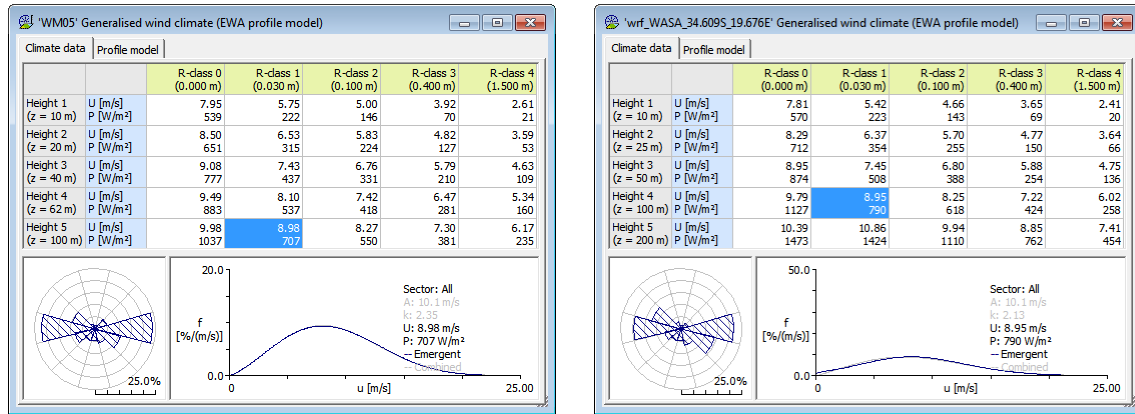


Figure 11. Sample wind atlas data sets for mast WM05, Napier, shown in WASP 11 software. Left-hand data set based on observations, right-hand data set based on WRF mesoscale modelling.

For application purposes – such as using wind atlas data sets for estimation of the energy production of a wind farm over the next 20 years or so – it should be borne in mind that the data sets may represent different time periods. The mesoscale data sets generally represent long-term estimates (WRF: 8-year period like WASA1: 2005-2013 or WASA2: 2010-2018) whereas the data sets based on observations represent a 2-year to 8-year period (WASA1 starting 2010 and WASA2 starting 2015).

It is essential in each project to evaluate how representative the selected data set is for the long-term climatology of the site in question. Reliable wind index information is not readily available for South Africa, so the predictions must be referenced to any or all long-term data sets available.

4.4 Topographical inputs

The terrain features that influence the wind flow close to the ground – and therefore determine how the generalised wind climate is transformed into the site-specific wind resource – are often categorized in three broad classes:

- Geometry of the terrain surface (elevation, slope, ruggedness, exposure, etc.)
- Surface characteristics of the terrain (land cover, roughness length, etc.)
- Near-by sheltering obstacles (houses, trees, shelter belts, etc.)

Coordinate systems used with these topographical data are described briefly at the end of this section.

4.4.1 Terrain surface elevation – height contour maps

An accurate description of the overall geometry of the terrain surface is a prerequisite for reliable modelling of the wind flow over the terrain. The most important feature is the elevation of the terrain surface above mean sea level.

The microscale model may require a height contour map for the flow modelling. This can be obtained by digitising the height contours from a standard topographical map; however, this is a labour-intensive and somewhat tedious process. Moreover, it may be impossible to find reliable and up-to-date maps for a given wind farm site. The contours can also be constructed from spot height elevations in a regular grid, so-called raster data.

Version 3 of the Shuttle Radar Topography Mission (SRTM, 2005) elevation data set has recently become available. This data set consists of elevation values for node points in a 3 or 1 arc-second (~ 90 or ~ 30 m) grid, derived from radar measurements made by the space shuttle Endeavour. These data cover all of South Africa and version 3 is a complete data set where voids and spikes are removed. Figure 12 shows an example of elevation maps derived from the SRTM data set.

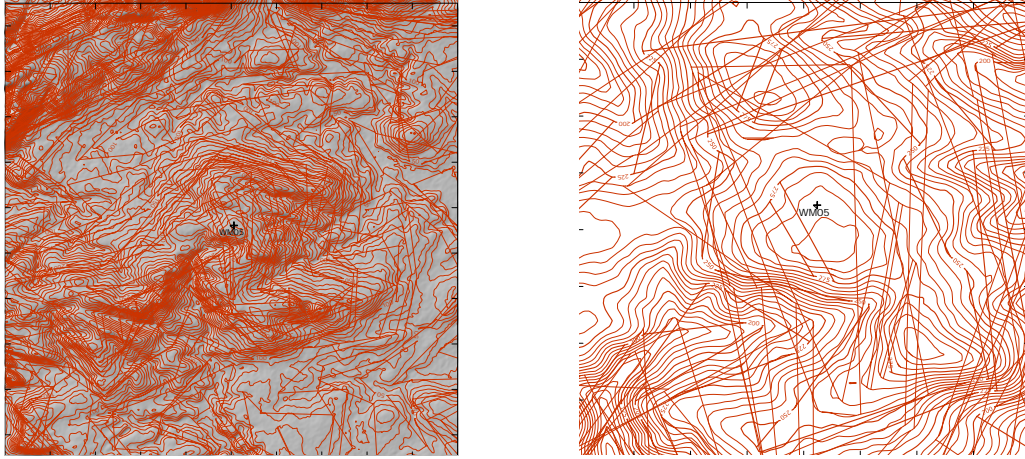


Figure 12. Elevation maps of the area around the meteorological mast WM05. Left-hand map covers an area of 20×20 km² with 10-m height contours; right-hand map covers an area of 4×4 km² with 5-m height contours.

Investigations in South Africa (Mortensen et al., 2014, 2018) and elsewhere show that maps derived from SRTM data are sufficiently detailed and reliable for most wind flow modelling purposes. However, the spot heights or height contours should be compared to other reliable maps of the area, if such exist – especially with respect to the height contours close to the site(s) of interest.

When it comes to actual planning and construction of a wind farm, more detailed maps may be required. These can be established by a number of other techniques; an example of a very detailed elevation map of a wind farm site in Egypt is given in Figure 13 (Mortensen et al., 2005).

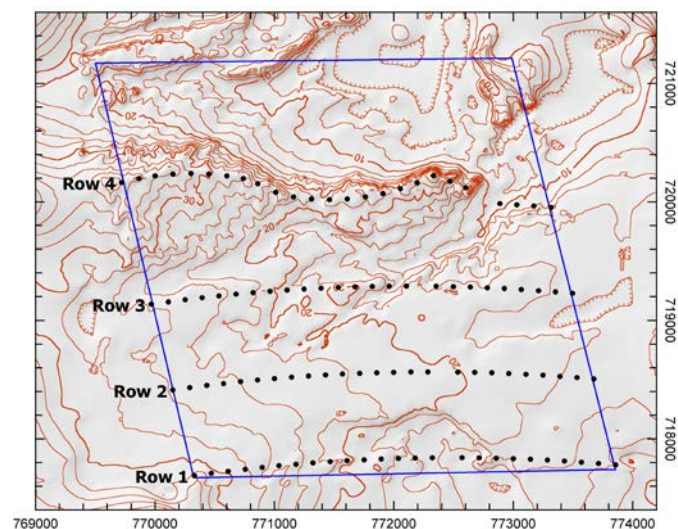


Figure 13. Elevation map of the Zafarana wind farm site in Egypt established by a site-specific survey employing kinematic GPS techniques. The height contour interval is 2 m. Four wind turbine groups, each of 25 600-kW wind turbines, are indicated by black dots.

In general, it is therefore straightforward to establish digital maps with 10- or 5-m height contours in most of South Africa. If spot heights from e.g. paper maps or raster data sets are considered as well, it will be possible to detail such maps in certain areas; but if a more detailed elevation description is needed, a site-specific survey of the terrain may be required.

The influence of the detail in the elevation description on the modelling of the wind flow – and thereby the estimation of the annual energy production – can be illustrated by using different maps of the same area; with different height contour intervals and detail. Examples are given by Mortensen *et al.* (2010) for three case study sites in China, where AEP predictions have been made with maps derived from SRTM data only and maps improved by adding details from large-scale paper maps. The regional wind climate and wind turbine type used for the predictions are the same in both scenarios. The analysis shows that the AEP predictions are not very sensitive to the elevation map for the three case study areas; the maximum difference found is on the order of 1%.

4.4.2 Land cover and roughness length – roughness maps

An accurate description of the land cover and roughness lengths of the terrain surface is another prerequisite for reliable modelling of the wind flow over the terrain. The most important land cover classes in South Africa are: farmland, scrubland, water surfaces, forests, bare soil and rock, and built-up areas. The overall land cover pattern of a particular area can be established from topographical maps, aerial photographs or satellite imagery. The most up-to-date and readily available information on the type and distribution of land cover classes stems from satellite imagery.

Evidently, the terrain descriptions should correspond to the scenario one wants to model. So, if historical data from a standard meteorological station are analysed, the maps (especially the land cover) should correspond to the terrain at the time of the observations. Since the wind data analysed here were measured from 2010-2018 and possible wind energy projects will be built in the near future, the elevation and land cover maps should correspond to present day conditions. Figure 14 shows an example of a roughness map derived from the ESACCI 2015 data set.

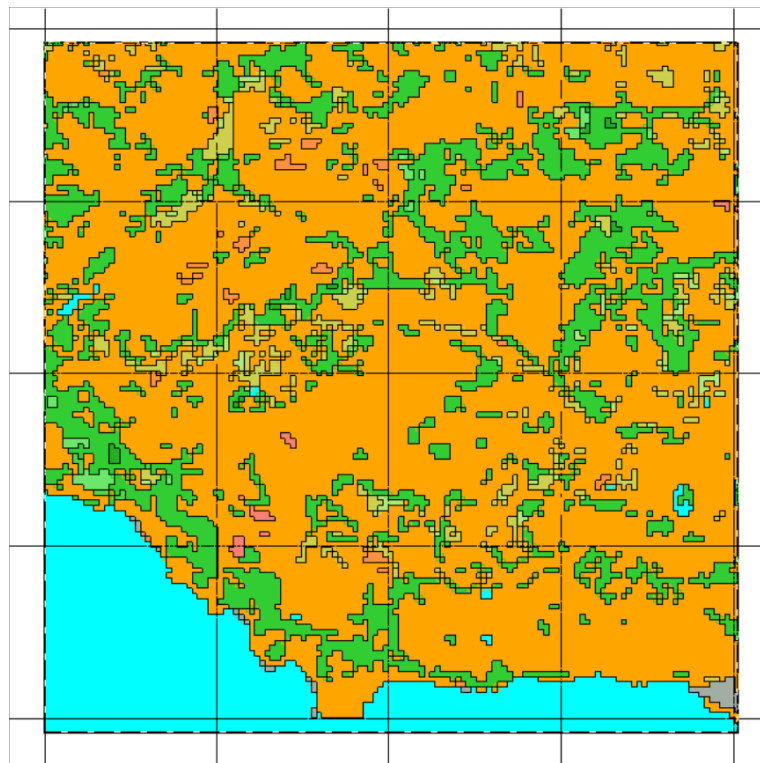


Figure 14. Roughness map of the area around the meteorological mast WM05, Napier. The map covers an area of 40×40 km² and the land cover classification is from ESACCI 2015 data.

The most common land cover type, corresponding to the 'background roughness length', consists of farmland or scrubland. It may be difficult to estimate the roughness length of such surfaces; however, it should be borne in mind that this estimate is most critical if the meteorological mast is low and less critical the higher the mast. Preferably, the anemometer used for predicting the wind turbine production should be mounted at a height comparable to the hub height of the proposed wind turbine. The sensitivity of changing the background roughness length by a factor of two (both lower and higher) was investigated by Mortensen *et al.* (2010). For predictions of wind energy production between 75 and 125 m a.g.l. from 70-m measurements, the sensitivity was found to be less than 2% in all three case studies.

In the present project, it has been found that reliable wind profile modelling can be obtained with a variety of land cover descriptions. However, it has also been found that a reliable roughness length classification is not sufficient; adjustments to the atmospheric stability must sometimes be employed too (Mortensen *et al.*, 2014). There seems to be a clear pattern over the WASA domain in these stability adjustments, but it has not been possible in the present project phase to describe this in sufficient detail. It is therefore strongly recommended to employ several levels of anemometry at measurement masts; in order to check the modelling of the vertical wind profile.

4.4.3 Sheltering obstacles

Sheltering obstacles are mostly man-made structures like houses, walls or fences. Shelter belts and rows of trees may also be quite common. However, the height of typical obstacles and their distance to possible wind farm sites suggest that it will only rarely be necessary to model these structures as sheltering obstacles. Instead, the obstacles can usually be treated as adding to the roughness of the areas in question.

The following rule of thumb may serve as a guideline when deciding whether to include nearby obstacles in the terrain as sheltering obstacles or as roughness elements:

- if the point of interest (anemometer or wind turbine hub) is closer than about 50 obstacle heights to an obstacle and closer than about three obstacle heights to the ground, the object should probably be included as a sheltering obstacle. In this case, the obstacle should not at the same time be considered as adding to the roughness of the terrain.
- if the point of interest is further away than about 50 obstacle heights or higher than about three obstacle heights, the object should most likely be included in the roughness description. In this case, the obstacle should not at the same time be considered as a sheltering obstacle.

A wind turbine with a hub height of 50-100 m a.g.l. and sited well away from buildings will therefore rarely experience shelter effects. Conversely, shelter effects may be quite severe for a meteorological station with a 10-m mast sited close to built-up areas.

4.4.4 Coordinate systems

Most of the information used in wind resource assessment and siting – and indeed much of the information needed for wind farm planning and development – is geo-referenced. The location of a given meteorological station, the elevation of the terrain, the extent and shape of significant land cover or roughness classes and the layout of a wind farm can only be described accurately by referring to the exact position or coordinates of the feature in question. Wind flow modelling requires accurate and reliable information on the coordinates of the inputs used. In WASP and other microscale flow models, all coordinates must be given in the same Cartesian, metric coordinate system.

Two coordinates systems (projections) are used in the reports of the WASA project: common geographical coordinates (latitude, longitude) and the Cartesian Universal Transverse Mercator (UTM) system. Both systems are referenced to the World Geodetic System 1984 (WGS 84) datum.

Figure 15 shows the geographical coordinate system – lines of equal latitude and longitude – for southern Africa. This system is not Cartesian and therefore not suited for microscale wind flow modelling or planning purposes. However, several input data are provided in this system, e.g. Google Earth images, other satellite images, Shuttle Radar Topography Mission elevation data, SRTM Water Body Data, Coastline Extractor data, etc.

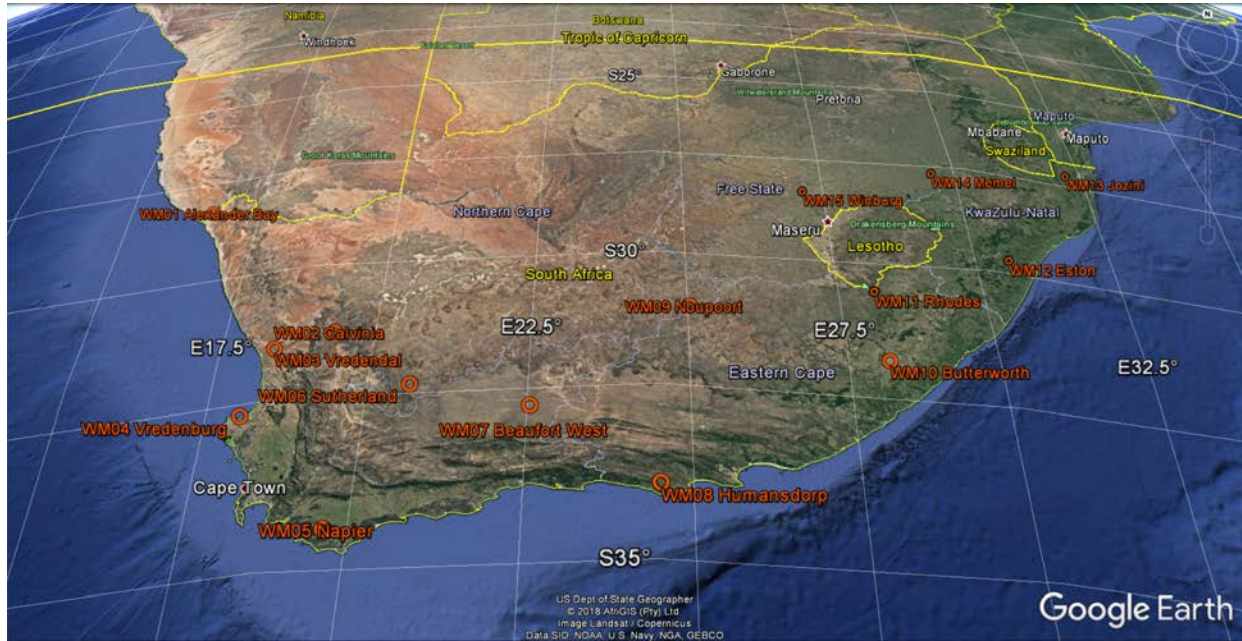


Figure 15. Google Earth image of southern Africa showing the geographic coordinate grid – latitude and longitude lines in degrees south and degrees east, respectively.

Figure 16 shows the Cartesian UTM systems used. Because the WASA domain spans almost 17 degrees of longitude, three different UTM zones must be used; these are shown by the grid lines in Figure 16 (zones 33, 34 and 35).



Figure 16. Google Earth image of southern Africa showing the three UTM zones covering the WASA Phase 1 domain: 33, 34 and 35. Each zonal coordinate system is Cartesian and the coordinates can be given in [m] or [km].

Each UTM zone has a local x-axis originating 500 km west of the central meridian of the zone. The y-axis originates 10,000 km south of the equator for all three zones. The meteorological station coordinates in the WASA project are referenced to either UTM zone 33, 34 or 35 (Mortensen *et al.*, 2014).

Transformation between different coordinate systems is quite complicated and must be performed using specialised software. The WAsP Map Editor and the Geo-Projection Transformer are two public domain software tools that can transform single points, lists of points and entire WAsP map files – using several different map projections and almost 150 different map datums.

Global Positioning System (GPS) devices also refer to a specific coordinate system. The default system in most receivers is (latitude, longitude) referred to WGS84, but this can be changed in a set-up menu. Coordinates downloaded from the GPS using some software may be referenced to WGS84, regardless of the setting of the GPS.

4.5 Application in wind energy projects

Mesoscale and microscale models resolve different features of the terrain and flow, and they are useful in different phases of planning and project preparation. The mesoscale model output should not be used directly for detailed planning or estimations, since it represents an abstraction, namely the “mesoscale wind” in a mesoscale terrain, which has to be transformed to the predicted near-surface wind speed and direction distributions by applying a microscale model. Application of mesoscale modelling for obtaining information about the predicted wind climate at a given location in South Africa therefore will use a *.LIB file generated from the mesoscale modelling as input to a microscale model such as WAsP, used according to recommendations.

However, in addition to providing the geographical coverage of the generalized wind climate for a large area like all of South Africa, mesoscale modelling has to be employed in order to enable assessment of the validity of the assumptions used for microscale modelling. The wind farm site may include an area with a large regional wind climate gradient, which would violate the microscale modelling assumption of constant generalised wind climate over the microscale modelling domain. The mesoscale modelling may furthermore be used to identify locations with large gradients and thus locations where an extended measurement programme will be advisable in order to avoid gross errors in wind resource and energy yield assessments.

The terrain features that influence the wind flow close to the ground – and thereby determine how the regional wind climate is transformed into the site-specific wind resource – are often categorized in three broad classes:

- The geometry of the terrain surface (elevation, slope, complexity, ruggedness, RIX, etc.)
- The surface characteristics of the terrain (land use or roughness length)
- Near-by sheltering obstacles (houses, trees, shelter belts, etc.)

As an example, the detail in the elevation description influences the modelling of the wind flow and thereby the estimation of the annual energy production (AEP).

In microscale modelling, an increase in height contour intervals from 2 to 10 m has been found to increase the contribution to uncertainties in AEP estimates by more than 5% – even in terrain with relatively little complexity or ruggedness. In more rugged, complex and mountainous terrain, the uncertainty increases and the dependency on accuracy and resolution of terrain data increases. To test uncertainties associated with microscale and mesoscale flow modelling as well as with terrain data it is generally recommended to carry out

- model parameter studies and adaptation of models to local conditions
- sensitivity analyses, site calibration and validation against measurements

Other aspects to be considered are

- wind climate variability within the time-frame of the data collection and the planned projects
- inter-annual variations, long-term averages and climate change
- man-made, large-scale effects on wind climate by changes in terrain and flow conditions due to the utilization of the land, especially building of new large wind farms and urbanisation.

In general, inter-annual variations relative to long-term averages are often seen to be of the order of 5-10% on mean wind speed. Wind climate variability differs however in different climate zones.

Longer-term wind data series that may be used to assess inter-annual variation and long-term averages are available from the global reanalysis data sets, but any such dataset must be used with care in a wind energy context. Global climate change modelling, rather than reanalysis, may be valuable in the evaluation of impacts of global climate change on wind farm AEP.

Regarding man-made, large-scale effects on wind climate, it should be noticed that the uncertainty due to any new large wind farm may be significant for its surroundings. Exact quantification may be difficult, but up to 20% loss in energy production has been seen. This aspect will be relevant for all large wind farm projects and thereby also in planning phases when assessing the potential energy production from wind and the consequential impact on the economics of a project.

4.6 Wind farm calculations

The wind resource map is one of the basic inputs in the wind turbine siting procedure and in the determining the wind farm layout. Figure 17 shows a sample layout for a 30-MW wind farm as analysed in one of the case studies. The wind farm layout should (alongside other criteria that may be decided by the project developer, owner and authorities) aim at maximising wind farm production, minimising wind farm wake losses and minimising the wind turbine structural loads.

Once the wind farm layout and turbine type have been selected, the wind atlas methodology (WAsP) can be used to estimate the potential annual energy production (AEP) from the wind farm, including wake effects. For this calculation to be reliable, it is important to use site-specific power and thrust curves for the wind turbine in question. Information on the average annual air density at the site is required; this may be calculated from site measurements of atmospheric pressure and air temperature, but WAsP 12 further employs a global model for air density.

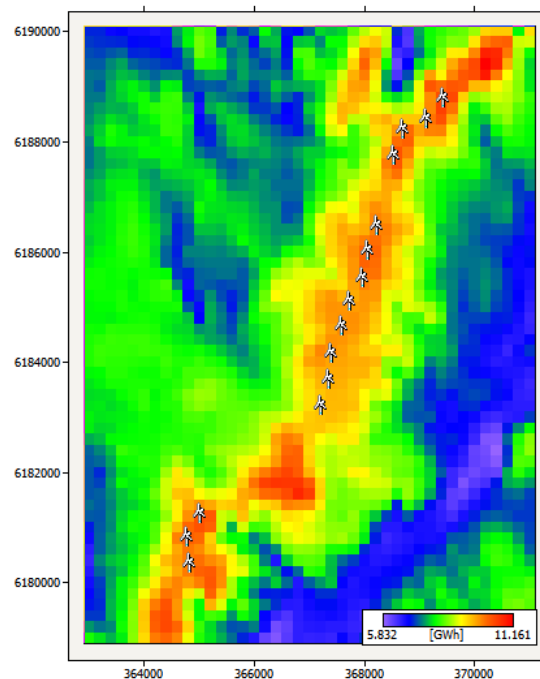


Figure 17. Sample layout for a 30-MW wind farm as analysed in one of the case studies.

4.7 Wind resource mapping

For a given wind farm site, the regional wind climate derived from the numerical wind atlas or a nearby meteorological station can be used to map the wind resource over the site. Examples are given in the case studies, where the mean wind speeds at 80 or 100 m above ground level have been estimated by means of the WAsP model in areas surrounding the masts. For wind farm sites located close to the masts the regional wind climate from the meteorological station may be used for the modelling as well as the regional wind climate files generated for the relevant mesoscale grid cells by the mesoscale modelling.

Even within fairly small and homogeneous sites, the estimated production easily varies by more than 20%, so for sites with ridges and other significant features, a very thorough site optimisation effort is essential.

Wind resource maps for any area in South Africa can be established in the same manner by using the regional wind climate statistics from the numerical wind atlas.

4.8 Reliability of wind resource estimates

The reliability of wind farm calculations, wind resource mapping from Observational Wind Atlases as well as of the validation of the Numerical Wind Atlas depend first of all on the quality of the data from the meteorological stations from which the wind statistics have been derived. The quality of the wind speed and direction measurements has to be assessed.

The quality concept is sub-divided here into accuracy, reliability and representativeness. The first two points – accuracy and reliability – reflect that the instruments should be accurate and remain accurate over the duration of the measurement campaigns. This requires an O&M program if the measurement campaign is longer than 1-2 years. A very important part of performing measurements is the quality assurance (QA) of the data. The representativeness of the data describes how well they can be expected to represent the long-term wind climate at the predicted site(s). Evaluation of the representativeness of the data involves the data duration, data recovery rate and distribution of missing data. Additionally, one should always evaluate how the data fit into the long-term wind climate, to avoid a possible “climate bias”, since the site data used often covers only a few years. Comparison to near-by long-term meteorological stations or long-term modelled data can be made, using a variety of methods.

Secondly, the reliability of wind farm calculations, wind resource mapping from Observational Wind Atlases as well as of the validation of the Numerical Wind Atlas depends on the complexity of the terrain; at the meteorological station as well as around the sites of interest. Finally, the geographical variability of the wind resource will necessarily add to the uncertainty of the estimates.

The reliability of estimating the spatial variation of the wind resource and any extrapolation or interpolation depends on the performance of the mesoscale modelling and the generation of the Numerical Wind Atlas. Assessments in quite some detail from the results of the mesoscale modelling of South Africa and the modelling domains are presented in the Mesoscale Report, using the 15 measurement stations WM01-WM15 as validation points. These results may not be sufficiently detailed and accurate for micro-siting and bankable production calculations, but they provide a fairly reliable picture of the large-scale spatial variations of the wind resource, although considerably more accurate and reliable in the parts of South Africa with less complicated terrain than in the parts with complex terrain.

4.8.1 The similarity principle

Current knowledge about the uncertainties in WAsP wind resource assessment may be summarised in the so-called *similarity principle*: Accurate predictions of wind climate and annual energy production based on observed wind climates require that the meteorological station (predictor) and the turbine site (predicted site) should be as similar as possible with respect to:

- Topographical setting
 - ruggedness (RIX index)
 - height above ground level
 - elevation above mean sea level
 - exposure, e.g. orientations of ridges
 - distance to significant roughness changes (for example, a coastline)
 - background roughness lengths
- Climatic conditions
 - regional wind climate (synoptic and mesoscale)
 - general forcing effects
 - atmospheric stability

With respect to WAsP, accurate predictions using the WAsP IBZ-flow model – and indeed most other wind resource assessment and siting models – may be obtained (Bowen and Mortensen, 1996) provided:

- the meteorological station and wind turbine site are subject to the same overall weather regime, i.e. that mesoscale effects are not significant or, if present, the two sites are affected in the same way,
- the prevailing weather conditions are close to being neutrally stable, and
- the surrounding terrain (of both sites) is sufficiently gentle and smooth to ensure mostly attached flows.

The latter requirement in particular has a significant impact on the accuracy of WAsP predictions in complex terrain; if the site is complex, WAsP CFD should be applied.

To what extent a similarity principle exists for the mesoscale modelling as well is not clear. Studies reported in the Mesoscale Report indicate that a relation can be established between uncertainties and terrain complexity.

5 Design wind condition

In addition to the predicted wind climate – the distribution of wind directions (wind rose) and the sector-wise distributions of mean wind speed – other wind conditions may be important for the design of a wind farm. Some of these characteristics have been measured directly at the project measurement stations; others must be estimated from the meteorological data.

5.1 A brief introduction to the IEC 61400-1 standard

The International Electrotechnical Commission provides the IEC 61400-1 standard for turbine safety (IEC 1999, 2005, 2009). The main principles are that manufacturers classify turbines and developers check that site conditions do not exceed the design limits of the class of the selected turbine.

5.1.1 Turbine classification according to IEC 61400-1

Edition 3 of IEC 61400-1 declares three turbine classes: I, II & III, each with a reference wind V_{ref} set to 50 m/s, 47.5 m/s and 37.5 m/s, respectively (IEC 2005). This reference wind is defined as a 10-min average wind speed at hub height. In addition, there are three turbulence categories A, B & C, each characterized by a reference turbulence intensity I_{ref} , which is set to 16%, 14% and 12%, respectively². The reference turbulence intensity is defined as the average turbulence intensity of the longitudinal velocity perturbations measured over random 10-min periods with a mean wind speed of 15m/s. A turbine is characterized by its wind class and turbulence category, e.g. a turbine for medium extreme wind and medium turbulence is classified as a class II_B turbine, see Table 7. There is an additional class S for which the manufacture specifies the reference wind and reference turbulence intensity. Class S is typically used for offshore turbines.

Table 7. IEC 61400-1 turbine classification scheme.

Wind Turbine Class	I	II	III	S
V_{ref} (m/s)	50	42.5	37.5	Values specified by the designer
A I_{ref} (-)	16%			
B I_{ref} (-)	14%			
C I_{ref} (-)	12%			

To verify that a turbine is of a given class it must be proven that it can survive a list of design load cases. These load cases are defined by combinations of:

- Turbine mode of operation – e.g. normal mode of production, normal start or stop, emergency stop, sudden grid failure, operation under yaw error etc.
- Load type - either ultimate load or fatigue load,
- Wind conditions – e.g. extreme wind, severe or normal turbulence, severe or normal wind shear or various gusts and wind direction changes.

The design wind conditions are specified by simple models which are parameterized by:

- The reference wind speed V_{ref}

² IEC 61400-1 Ed. 2 (IEC 1999) used a slightly different classification scheme.

- The reference turbulence intensity I_{ref}
- The turbine hub height z_{hub}

An example of a load model is the normal turbulence model (NTM) which is applied for fatigue load simulations. In here the longitudinal velocity perturbations are modelled as

$$\sigma_1 = I_{ref} \left(\frac{3}{4} V_{hub} + 5.6 \text{ m/s} \right)$$

This model has wind-speed dependence and the intention is to model not the average turbulence level but the 90% percentile of a distribution of turbulence conditions. Reasons for such variation include variable atmospheric stability and trends in mean wind speed. The NTM turbulence is referred to as representative turbulence³. Another example is the normal wind profile (NWP) defined as

$$V(z) = V_{hub} \left(z/z_{hub} \right)^\alpha$$

The shear exponent α in this profile is set to 0.11 for extreme load test and 0.2 for fatigue loads. The standard defines several gust and wind-direction change load cases. These are specified by design models which all are parameterized by V_{ref} , I_{ref} and z_{hub} .

5.1.2 Site assessment according to IEC 61400-1

The general principle of IEC 61400-1 site assessment is that actual wind conditions must be less severe than assumed in the turbine design class. The following criteria apply:

- The 50-year extreme wind must be lower than the reference wind of the turbine class;
- Flow-line inclination at hub height must be less than $\pm 8^\circ$ for all wind directions;
- The average wind-shear exponent α at hub height must be positive but less than 0.2. The reason for avoiding excessive shear is the risk of enhanced fatigue damage and the reason for avoiding negative shear is the risk of blade-tower interaction;
- The wind-speed distribution must be lower than the distribution used for turbine classification in a certain wind speed range. This range is either defined as 60% of rated wind speed to turbine cut-out wind speed or, in case the power curve is unknown, defined as 0.2 to 0.4 times the reference wind of the turbine class. More exposure in this wind-speed range would enhance fatigue damage;
- The effective turbulence intensity, see below, must be lower than the applicable IEC model in a range from 60% of rated wind speed to the cut-out velocity. The applicable model is either characteristic or representative turbulence intensity depending on whether the turbine type is classified according to edition 2 or 3 of the standard.

These criteria apply to individual turbine sites. An additional rule states that turbulence must be scaled by a safety factor if the terrain is complex and the turbulence intensity has not been measured. The reason is that turbulent kinetic energy in complex terrain is redistributed among the three velocity components. Terrain complexity is evaluated by criteria based on terrain slopes in the area around each turbine site.

5.1.3 Effective turbulence intensity

Fatigue loads for turbine classification are simulated for a range of wind speeds using the representative turbulence intensity. However, due to non-uniform surface roughness the turbulence intensity will, however, often depend on wind direction. Turbulence from wakes of neighbouring turbines

³ IEC 61400-1 Ed. 2 defined a slightly different measure called characteristic turbulence intensity. It was based on mean plus standard deviation instead of the 90% level of Ed. 3.

in wind farms will contribute significantly to the directional variation of the turbulence intensity. IEC 61400-1 Ed. 3 has an Annex D suggesting an optional model for the effects of wake turbulence – see also the detailed description of Frandsen (2007). In this model an effective turbulence intensity is defined as a constant turbulence intensity assumed to cause the same material damage as variable turbulence from all directions.

$$I_{\text{eff}}(u) = \left[\int_0^{2\pi} p(\theta|u) I^m(u, \theta) d\theta \right]^{1/m}$$

In this formula the Wöhler exponent m is a material constant, which is approximately $m=10$ for glass fibre. Annex D includes a simple model for the wake turbulence. Here, wake turbulence is modelled as a combination of background turbulence and added turbulence.

$$I_{\text{wake}} = \sqrt{I_{\text{ambient}}^2 + I_{\text{add}}^2}$$

The added turbulence intensity in the new IEC 61400-1/A1 amendment (IEC 2009) is modelled by

$$I_{\text{add}} = \frac{1}{1.5 + 0.8 \Delta x / D \sqrt{C_T(u)}}$$

Here Δx is the distance to a neighbour turbine, with diameter D and thrust coefficient C_T at wind speed u .

5.2 Assessment of wind conditions

5.2.1 Extreme wind speed

An extreme wind is defined by an averaging period and a recurrence period. The latter period is the expected waiting time for an event, which exceeds the extreme wind level. The IEC standard refers to extreme winds with 10-min averaging periods and 50-year recurrence periods. By fitting an extreme-wind model, typically a Gumbel distribution, to the observed extreme winds it is possible to extrapolate the statistics to the specified recurrence period, also when this is longer than the observation period. The accuracy of this extrapolation depends on the number of observation years and the slope parameter of the fitted Gumbel distribution. The IEC standard recommends a minimum of seven years. Furthermore, the Gumbel fit slope parameter is typically larger when modelling wind climates affected by tropical storms than when modelling continental or extra-tropical extreme wind climates. This leads to extra extreme-wind uncertainty.

According to the IEC standard, the extreme wind must be estimated at individual turbine sites. For this purpose we first use a micro-scale flow model to predict site-specific winds, then we fit local Gumbel distributions, and finally we extrapolate to local fifty-year extreme wind speeds. The reason for this procedure is that individual sites have different wind speed-up factors for winds coming from different wind directions.

Unfortunately, most wind energy projects do not have local wind observations of sufficient duration for extreme wind prediction. An alternative, which is implemented in the WAsP Engineering program⁴, is to use the wind atlas method to transform extreme wind climates at the reference site to the extreme wind climate for the wind energy project. The reference site should have a climate similar to that of the wind energy site. The procedure is to prepare two WAsP Engineering projects modelling the terrain around the reference mast and around the wind energy project, respectively. The first project is used to

⁴ See <http://www.wasp.dk/weng>

transform observed extreme wind climate to a generalized extreme wind climate free of local effects. This generalized extreme wind climate is stored on a file, which is loaded in the second project where it is used to predict extreme wind climates at individual turbine sites. If no representative observations of sufficient duration and quality can be found, a generalized extreme wind climate can be generated based on meso-scale models and reanalysis data.

5.2.2 Flow-line inclination

This can be calculated by a micro-scale flow model, e.g. that of WAsP Engineering. The IEC standard also allows use of terrain inclination instead of flow-line inclination as this is considered a conservative estimate.

5.2.3 Wind shear exponent

This can be evaluated by fitting a power law to micro-scale flow model results. WAsP Engineering calculates the shear exponent by the speed and its derivative at the hub height using the relation

$$\alpha = \frac{z_{\text{hub}}}{u_{\text{hub}}} \left. \frac{du}{dz} \right|_{\text{hub}}$$

5.2.4 Wind speed distribution

This distribution is calculated by WAsP.

5.2.5 Effective turbulence intensity

Effective turbulence intensity can be calculated by the Windfarm Assessment Tool⁵ (WAT), which is based on the Frandsen (2005) model and uses a combination of model results from WAsP and WAsP Engineering. The calculation includes the conditional wind rose, i.e. the wind direction distribution given the wind speed, which is estimated by a WAsP wind climate.

$$p(\theta|u) = \frac{p(u|\theta)p(\theta)}{p(u)} = \frac{p(u|A_j, k_j)fr_j}{\sum_{i=0}^{N-1} p(u|A_i, k_i)fr_i}$$

In this formula frequencies of occurrence fr_i are defined sectors with index i and the Weibull distributions in these sectors are

$$p(u|A_i, k_i) = (k_i/A_i)(u/A_i)^{k_i-1} \exp\left[-(u/A_i)^{k_i}\right]$$

A problem with estimating effective turbulence intensity in WAT is that the background turbulence intensity modelled by WAsP Engineering is valid only for steady flow and neutral atmospheric stability and it lacks random variation among 10-min periods. Thus, the WAsP Engineering turbulence prediction will typically be smaller than the representative turbulence intensity, which should be a measure of 90% percentile of a scattered distribution. WAT has a method for correcting the WAsP Engineering predictions by observed turbulence intensity statistics based on data from a reference mast near the turbine sites.

5.2.6 Gust statistics

A gust is a sudden increase in wind speed, which should not be mistaken for an extreme wind, which is a term referring to average wind. The spatial scale of a gust relates to its duration, so the gusts which are considered significant for wind turbine design have durations of the order of three seconds. Gusts are both important in the extreme wind situation and at moderate wind speeds where the turbine is operating. If turbulence is considered a Gaussian process, it is possible to calculate the most likely maximum gust in a 10-min periods. Extreme gusts will, however, typically deviate from the Gaussian

⁵ See <http://www.wasp.dk/wat> and Nielsen *et al.* (2009)

model as they are associated with rare meteorological phenomena like downbursts of high-altitude winds inside a thundercloud. This can be modelled with mesoscale models such as WRF.

The IEC 61400-1 site assessment rules will normally not include gust analysis. Even so, it might be a good idea to add gust detection to a field measurement system. This does not involve extra instruments only additional processing by the data acquisition system. The maximum and minimum excursion of a 3-sec moving average filtered cup anemometer signal from its mean value is of primary interest. Deviation from predictions by Gaussian theory could indicate flow separation from upwind terrain features. Analysis of pairs of signals are also of interest, e.g. wind shear detected by two vertically separated cup anemometers or wind veer detected by two wind vanes. The extreme-wind assessment is normally based on the 10-min average wind with fifty-year return period. It is permissible to make an alternative assessment based on 3-sec gusts with fifty-year return period, but then the reference wind used for comparison must be enhanced by 40%.

6 Case studies

6.1 Introduction

The WASA Work Package 4 on Application has made High-Resolution Wind Resource Mapping of the entire South Africa and some case studies in order to provide data and information for wind energy development in South Africa as well as to illustrate the various aspects of possible applications of the WASA project results. These are also used for the seminars and the application training course material. The WASP project WWH files and input files used for these case study calculations are downloadable from <http://wasadata.csir.co.za/wasa1/WASAData>.

The case studies show uses for wind energy planning and energy yield assessment of wind farms to:

- Demonstrate specific uses of the WASA data
- Show certain features of wind resource assessment
- Indicate understanding needed when interpreting results
- Serve as inspiration for exploring more about wind atlases

Please bear in mind:

- They are not necessarily a suggestion of a good wind farm location
- Aspects other than wind resource have not been reviewed
- Case studies are not intended to be a course in the use of wind resource assessment software

6.2 Case study – Planning

A typical use of the WASA data is for local planning for wind energy by a province, region or municipality and as input to assessing the wind resources in the planning area in order to:

- Understand the potential for wind energy
- Identify where the best areas are physically located
- Know more as background for choice of planning approach and selection of development zones
- Investigate any possible relations to other land uses

A map of the wind resources for any given area surrounding one mast can be generated from local measurements as shown in Figure 18 – in this case WM05. Such calculations are available at all WASA masts (WM01-WM15) downloadable from the WASA web-sites and reported in the microscale modelling report. The WASA team has assessed and selected one common set of input data for terrain elevation and land cover with one common translation table from land cover to surface roughness.

Since especially this approach to determining the local surface roughness will result in varying uncertainties, users are advised to consider applying their local knowledge and adaptations if and where this would locally be a better representation of the reality on the site and area of interest.

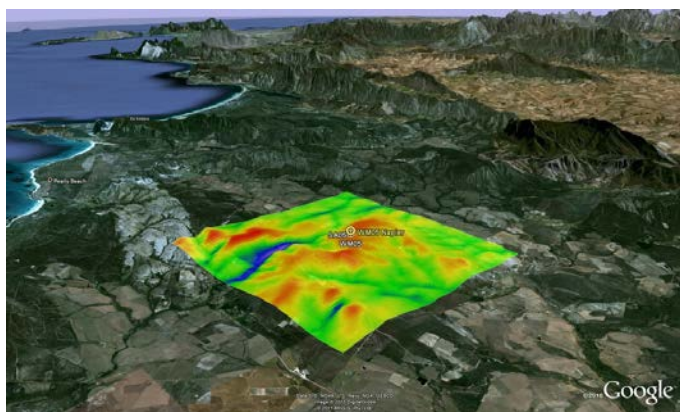


Figure 18 Wind resource map calculated for the surroundings of WASA mast WM05.

The calculation area based on measured wind data from one mast may in principle be extended to any given size area, which however is **NOT** recommendable. Most areas would have significant to large mesoscale effects and wind resource gradients, which would not be accounted for in such microscale modelling of large areas.

However, from the WASA Numerical Wind Atlas (NWA) data it is possible to make wind resource maps of similarly large regional areas that include the regional mesoscale effects and gradients across the area. It is recommended to use the NWA in combination with the validation that has been made by the NWA at the location of the WASA masts.

The latest 2018 set of NWA data (LIB-files) are available from the WASA download site for every 3.3 km × 3.3 km. Based on selected NWA LIB-files, the wind resource in the local 3.3 × 3.3 km area can be modelled using a microscale modelling tool like WAsP. A large-scale map of estimated annual mean wind speed at 100 m (or any other height) above ground level may thus be produced by repeating the microscale modelling for every NWA grid point, i.e. every 3.3 km × 3.3 km. A “tile” will be made for each LIB file grid point, and by patching all these together a map may be constructed. Such a map will have discontinuities along tile borders, but inside each tile, these wind resource values will take account of regional mesoscale effects, which is the purpose of applying the NWA. The result still contains uncertainties due to the NWA methodology; however, this has been assessed through the validation of the NWA and may be assessed independently by any user of the NWA who can apply the user’s own local wind data at the user’s own site.

The LIB-files and guide for downloading can be found on the WASA download site <http://wasadata.csir.co.za/wasa1/WASAData>. The relevant LIB-files for the area may then be selected and downloaded individually or, alternatively, LIB-files for the entire WASA domain can be downloaded.

Microscale modelling of an area than larger one tile may be achieved e.g. in WAsP by building the appropriate WAsP workspace as shown in Figure 19 and Figure 20.

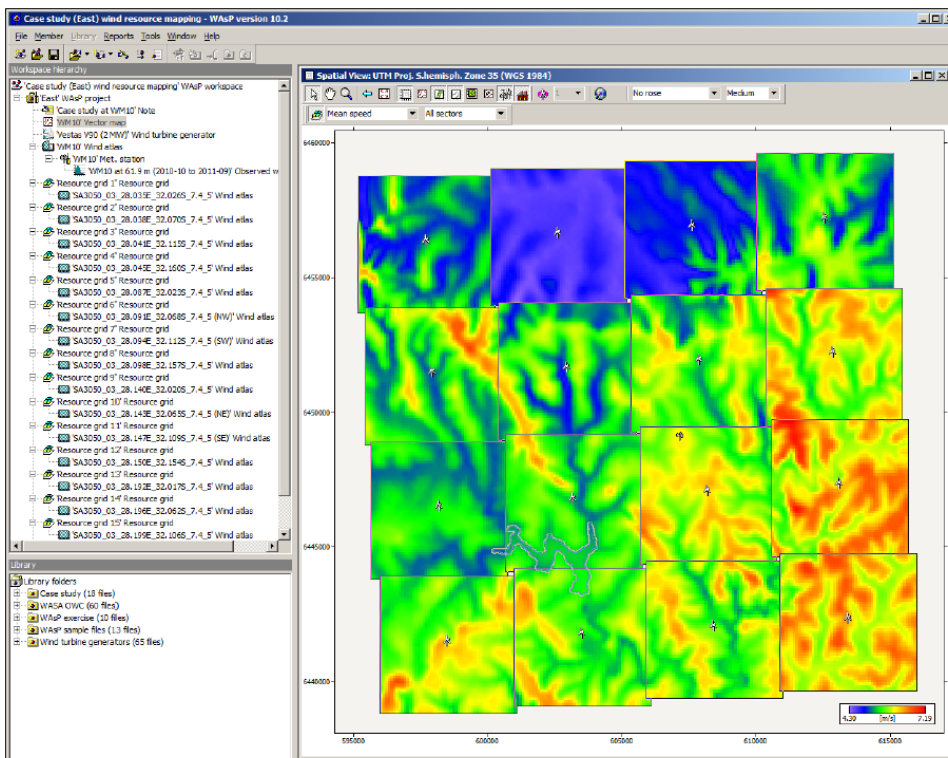


Figure 19 WAsP tiles calculated from WASA NWA LIB-files.

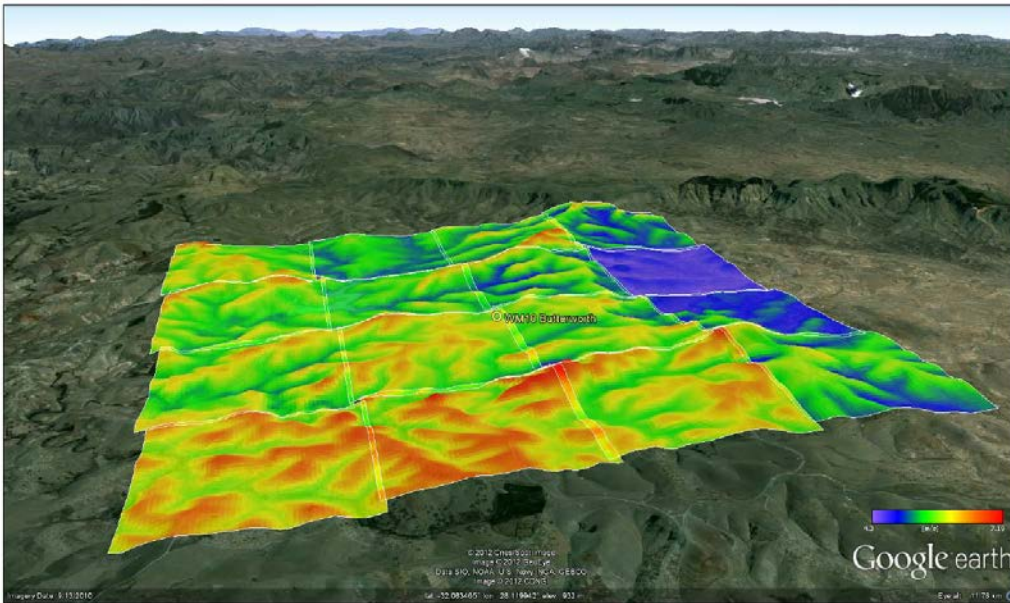


Figure 20 Wind resource tiles overlaid onto a Google Earth image.

So, microscale modelling of wind resources based on the WASA NWA may be done for any region or local area of any size and resolution, applying terrain elevation and surface roughness data that is either user defined or in accordance with the approach specified by the guidelines available on the WASA download site.

6.3 High-resolution microscale modelling of the entire South Africa done by WASA

Mapping the wind resources manually tile-by-tile using WASP for a very large region or for the entire WASA domain is a large task. The WASA NWA has over 170000 virtual masts (LIB-files or GWC-files) in the entire South Africa in the WRF run for South Africa. It has not been part of the project to microscale model all these manually.

However, the WASP software team has developed a “WASP Resource Mapping Tool” that can automate the process. The additional benefit is that it also has an interpolation approach so that the discontinuities along borders between tiles are eliminated. This “WASP Resource Mapping Tool” is not yet available as a commercial tool, but it is in accordance with project plans applied in the WASA project.

Applying the “WASP Resource Mapping Tool”, the mean wind speed at 100m for a grid spacing of 250m across the entire WASA domain was produced. Input data were:

- 170 000 LIB-files (GWC data) from the 3.3 km × 3.3 km WASA NWA
- Terrain and roughness information of the whole of South Africa
- Elevation data from Space Shuttle Topography Mission, SRTM+, NASA version 3
- Land cover and roughness from 300-m land cover grid derived from ESACCI 2015, version 2.0.7, applying Transformation table for z_0 aligned with Global Wind Atlas 3

The output is shown in Figure 21. As the modelling is done by WASP, other outputs are also available e.g. mean wind power density, terrain ruggedness index, and elevation data.

It should be noticed that particular care should be taken in complex terrain when applying these maps and results generated by the WASP IBZ model. An indication of areas with a high degree of complexity in the form of steep slopes and ruggedness may be found in the available Ruggedness index (RIX) map - see Figure 22.

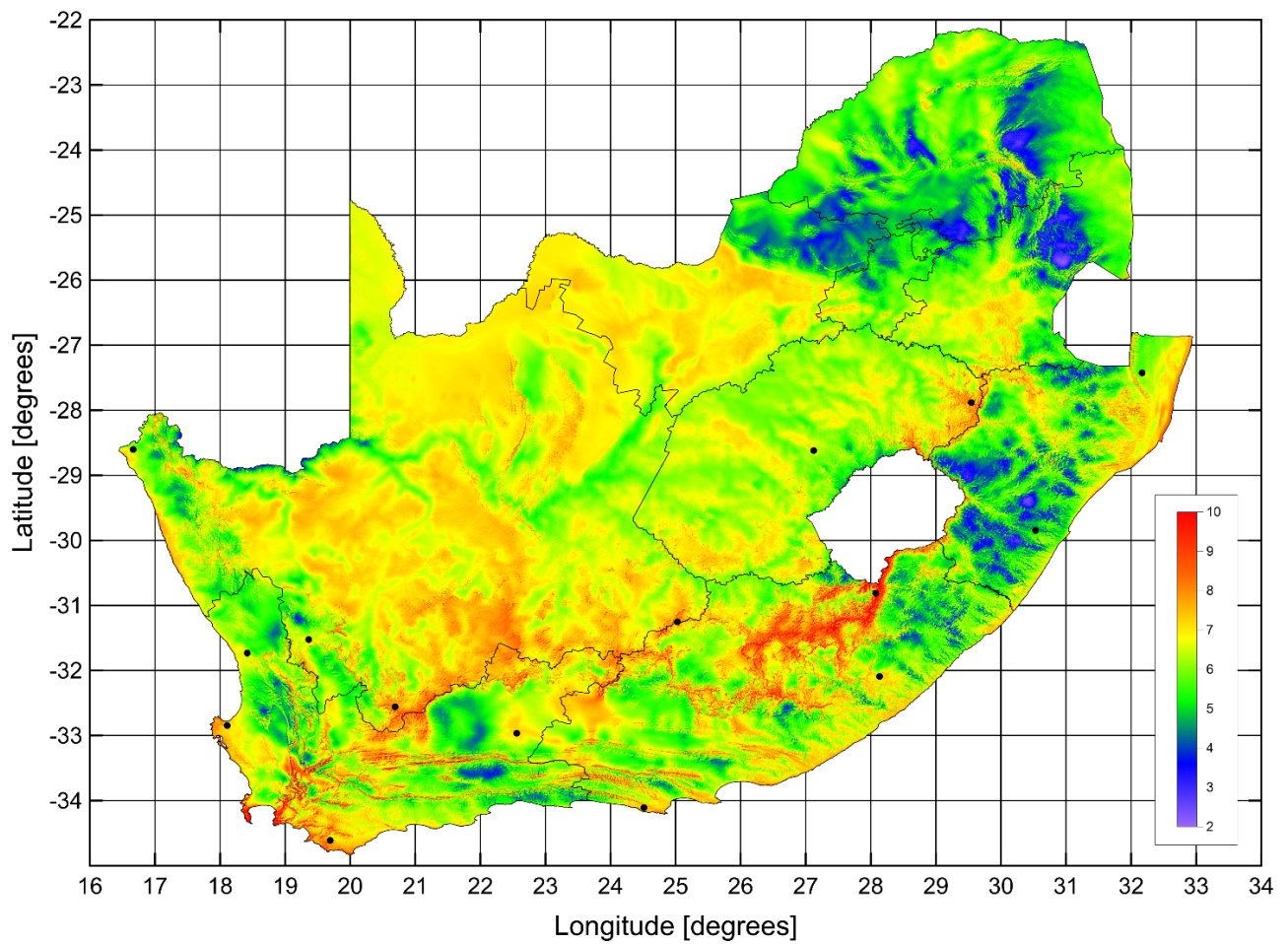


Figure 21 High-resolution wind resource map for the entire South Africa – mean wind speed (m/s) at 100 m a.g.l. with a grid spacing of 250 m.

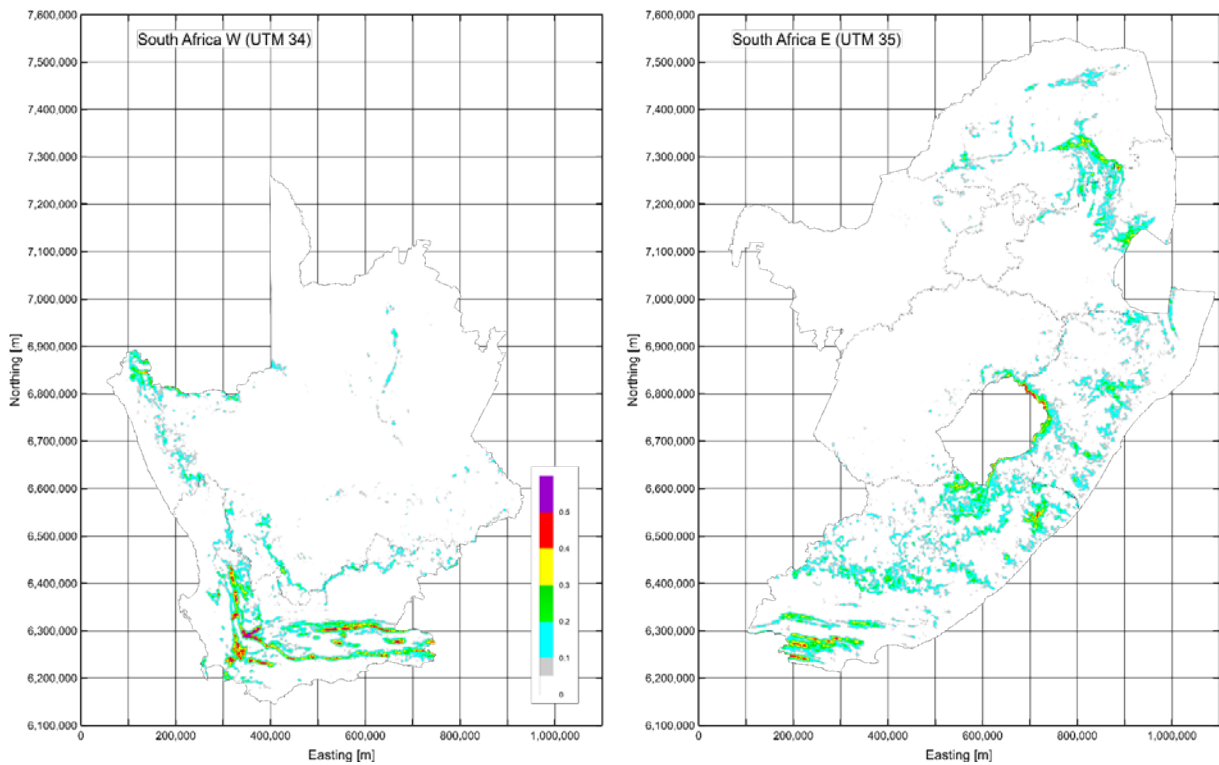


Figure 22 Ruggedness index (RIX) map.

6.4 Microscale modelling approach for planning purposes – summary

In summary, wind resource mapping for planning purposes in a particular area may be

- a) GIS-type data sets (*.ASC) downloadable from <http://wasadata.csir.co.za/wasa1/WASAData> for the entire South Africa as the available in a grid spacing of 250 m.
 - a. High-resolution wind resource map for the entire South Africa – mean wind speed (m/s) at 50, 100 and 150 m a.g.l.
 - b. Mean power density at 50, 100 and 150 m a.g.l.
 - c. Air density map
 - d. Elevation map -- 100-m void-filled elevation grid from space shuttle Endeavour (SRTM+, NASA version 3).
 - e. Land cover and roughness from 300-m land cover grid derived from ESACCI 2015, version 2.0.7, applying transformation table for z_0 aligned with Global Wind Atlas 3.
 - f. RIX- index map
- b) Generated as 3.3 km × 3.3 km tiles applying microscale modelling using the WASA NWA through the following steps:
 - Identify area to be mapped
 - Identify NWA grid points and download GWC data (LIB-files)
 - Make terrain maps for the area
 - Elevation (orography)
 - Land cover (roughness)
 - Import maps and wind data into modelling software (e.g. WAsP)
 - Run model (e.g. WAsP) to obtain resource maps as required for all 3.3 km × 3.3 km tiles covering the area to be mapped

All data and a guide are available on the WASA download site wasa.csir.co.za.

6.5 Case studies – Wind farm energy yield

This report has three selected case studies for illustration of aspects of applying the WASA. The locations are near Butterworth (WM10), Rhodes (WM11) and Napier (WM05) – indicated in Figure 23. These and more case studies can be found and further explored on the WASA web sites.

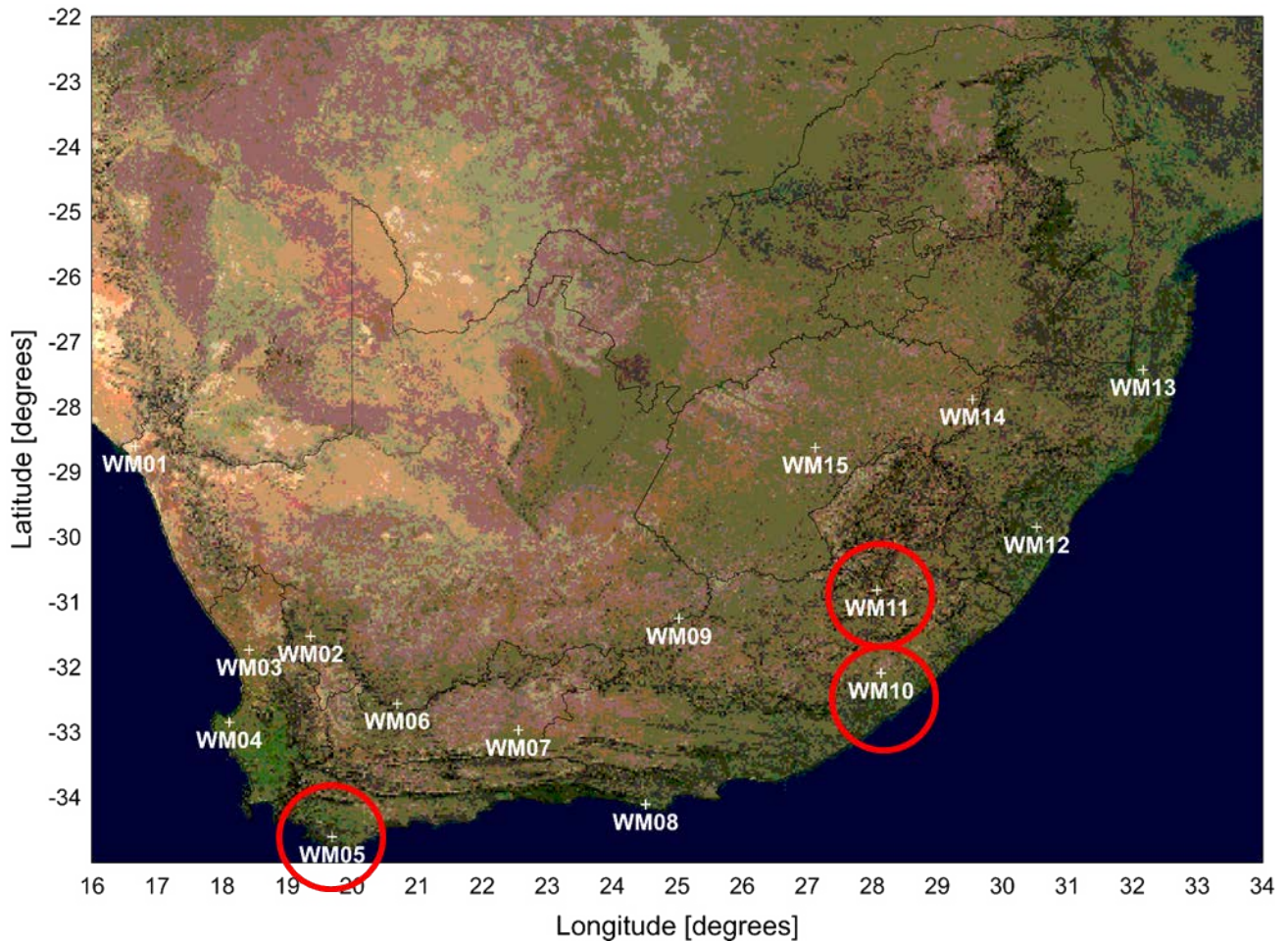


Figure 23 Approximate location of case study area

The assessment of the wind farm energy yield is a key process in wind farm development. The case studies are meant to show how WASA data can help with input to assessing the wind resource in the process of making a good wind farm project or in other words:

- How good is the wind resource at a given candidate site?
- How well do we know the wind resource at a given site?
- How would different wind farm layouts, wind turbines, and wind farm capacities affect the analyses and estimate of AEP?

It should be noted that a WASA NWA-based estimate of the wind farm AEP will not make the project bankable, but it will contribute to understanding and deciding what further steps are necessary.

6.5.1 Butterworth (WM10)

The Butterworth site and surrounding terrain is expected to allow reasonably reliable modelling by the linearized WASP IBZ microscale model as confirmed by the validation – see *Table 5*.

Figure 24, Figure 25 and Figure 26 show the observed (measured) wind climate compared to the predicted wind climates found for the measurement point applying the 4 nearest NWA LIB-files. There is a small bias from all of the 4 NWA grid points.

This case study demonstrates how the potential Annual Energy Production (AEP) of a wind farm can be estimated using the WASA NWA.

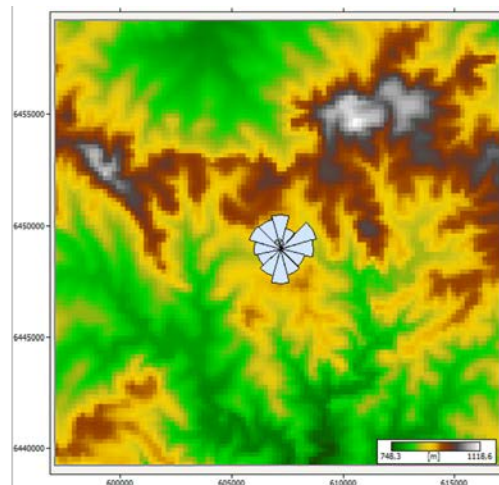
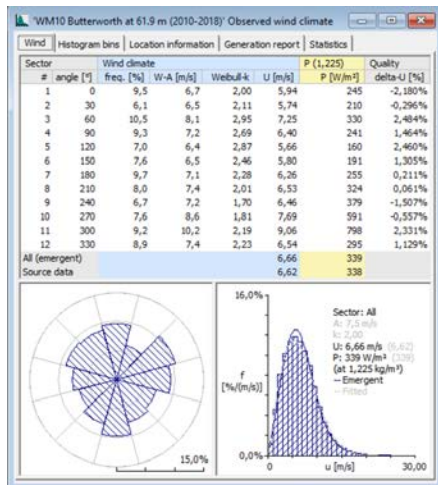


Figure 24 Observed Wind Climate (WM10).

	Predicted Wind, U1	U1-U0
	[m/s]	[%]
NWA1 (NW)	6,80	2,1%
NWA2 (SW)	6,76	1,5%
NWA3 (NE)	6,94	4,2%
NWA4 (SE)	6,95	4,4%
MAPE		3,3%
Mean bias		3,0%

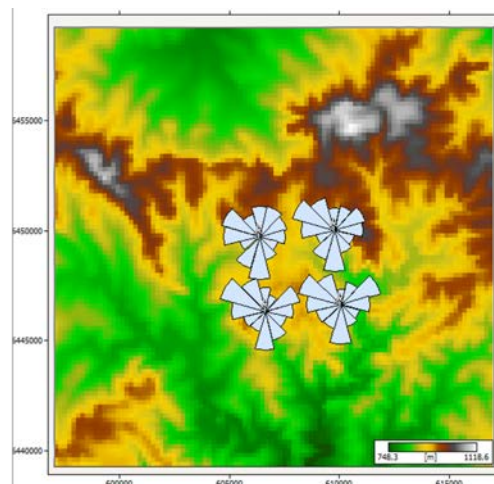


Figure 25 Predicted Wind Climates using WASA-NWA (WM10).

	Predicted AEP
	[GWh]
NWA1 (NW)	70.15
NWA2 (SW)	68.98
NWA3 (NE)	72.05
NWA4 (SE)	72.84
Mean	71.0±1.5

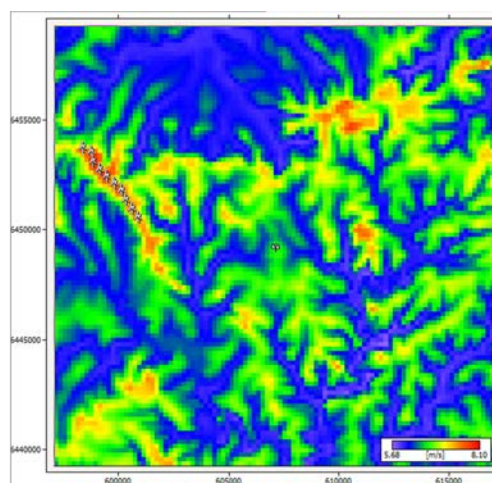


Figure 26 Wind farm siting (WM10).

6.5.2 Rhodes (WM11)

The Rhodes site and surrounding terrain is complex and steep slopes occur all around the site. The ruggedness index RIX at WM11 = 11%. This makes it fundamentally different from Butterworth and in fact from all other WASA mast sites, which all have low ruggedness index (RIX) numbers. It is therefore expected that applying the simple WASP IBZ model would present some difficulties as also confirmed by the validation – see *Table 5*.

Figure 27 and Figure 28 show the observed (measured) wind climate compared to the predicted wind climates found for the measurement point applying the 4 nearest NWA LIB-files. This exercise has been done applying first the WASP IBZ model, resulting in large bias and spread. When applying the WASP CFD model, the bias is reduced significantly, but the spread less so. Further studies could most likely have determined how to reduce the spread by applying the NWA grid points most similar to the exact mast location.

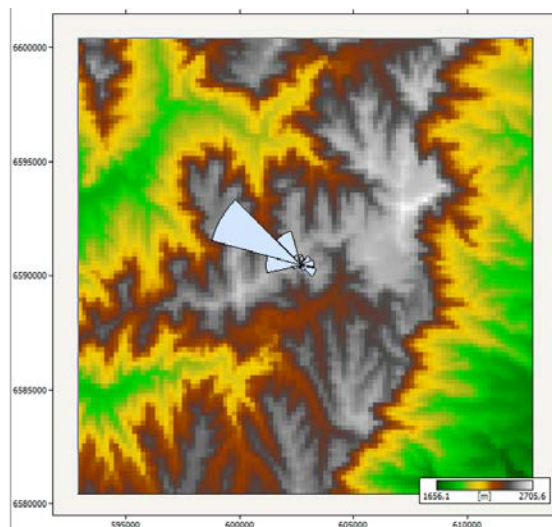
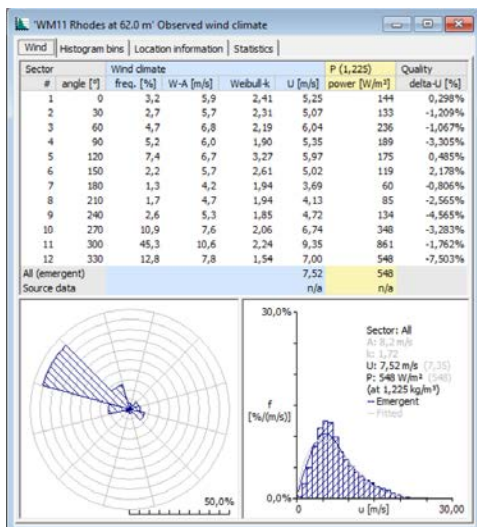


Figure 27 Observed Wind Climate (WM11).

	Predicted WASP IBZ, U1	WASP IBZ U1-U0	Predicted WASP CFD, U2	WASP CFD U2-U0
	[m/s]	[%]	[m/s]	[%]
NWA1 (NW)	8,0	6,6%	6,9	-8,4%
NWA2 (SW)	8,4	11,7%	7,1	-5,1%
NWA3 (NE)	9,2	22,3%	7,8	3,1%
NWA4 (SE)	10,1	33,9%	8,6	14,2%
MAPE		21,4%		8,8%
Mean bias		18,7%		1,0%

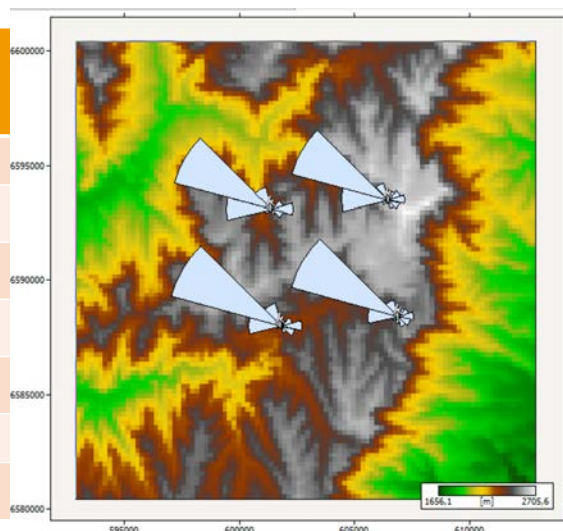


Figure 28 Predicted Wind Climates Using WASA-NWA (WM11).

This case study demonstrates how the WASA NWA can be used, carefully, for complex sites using WASP CFD when necessary.

6.5.3 Napier (WM05) and wind farm at Stanford

A case study called “Case study wind farm at Stanford” has been made and the calculations have been performed in WAsP using WAsP version: 11.01.0016 back in 2014. This case study has now been updated using WAsP 12, and is available on the WASA download site. This case study was reported in detail in the 2014 report, but we repeat briefly the main points here as they are still relevant and serve as a good illustration of the use of WASA in regions with a gradient in the wind climate.

Two WAsP calculations have been made for the Case study wind farm at Stanford:

- Applying the WASA NWA LIB-files in the best possible way – i.e. for each wind turbine in the case study the LIB-file nearest to it is identified and used in the WAsP modelling representing the local wind climate.
- Applying the wind climate determined at the WM05 location based on three years of wind measurements at the mast location as input to the WAsP modelling at all wind turbine sites.

Both these WAsP workspace files are available on the www.wasa.csir.co.za website. These files are “Case study wind farm at Stanford - with WRF LIB-files.wwh” and “Case study wind farm at Stanford - with WM05 LIB-file.wwh”, which contain all maps and input data used for the calculations.

By comparing the results of the two different sets of WAsP calculations for the “Case study wind farm at Stanford”, it is evident that there is a significant impact of whether the calculations are based on the measurements at WM05 or whether they are based on the WASA NWA. The Table 8 below shows a summary of the two wind farm AEP calculations.

Table 8. Comparison of Net AEP of the case study wind farm at Stanford.

input to WAsP	Net AEP* “Stanford case”
LIB-file from WM05 measurements	149 GWh/y
Several LIB-files nearest to each WTG – WRF based NWA	117 GWh/y
Over-estimation when using WM05	27 %
* At simple assumptions incl. 100% availability, no losses, standard air density and standard WAsP parameters	

In view of the results of the WASA NWA validations at WM05 – seen in the Table 9 below – it appears that the WRF-based NWA seems to be accurately representing the real wind as measured at the WM05.

Table 9 Validation of WASA NWA at WM05.

	OWA [m/s]	WRF [m/s]	Difference WRF
WM05	8.98	9.04	0.67%

The uncertainty of the AEP for the case study wind farm at Stanford determined by the WASA NWA LIB-files is therefore most likely reasonably small.

The difference of 27% between the AEP determined from the WM05 measurements and the estimate determined based on the WASA NWA can most likely be attributed to regional mesoscale effects and the difference in the wind climates between the mast location and the wind farm location just 20 km to the west-north-west. The difference in the mesoscale wind climate can be seen in Figure 29, which shows the wind farm plotted on the generalised LIB-file values of annual average wind speed at 100 m above flat ground level at 3 cm roughness for each 3 km × 3 km WRF grid cell.

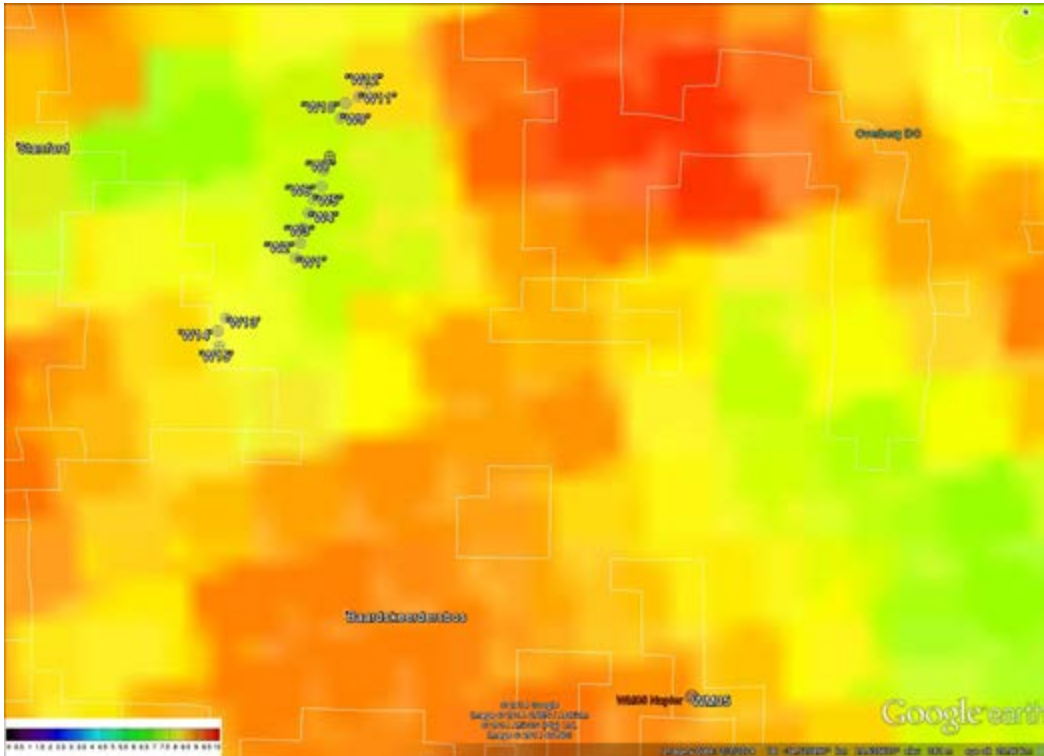


Figure 29 Case study wind farm at Stanford - plotted on WASA NWA LIB-file values for each 3 km x 3 km WRF cell.

The case study site is still a quite good wind farm site from a wind resource point of view, which is seen in Figure 30. This shows the high-resolution wind resource values of annual average wind speed at 100 m above ground level resulting from the microscale modelling. The reason for the good wind conditions found at the case study site is very much due to the local hills and the speed-up effect they generate, and which is captured by the microscale modelling, whereas the mesoscale model does not see this hill due to its averaging of topography in its 3 km × 3 km cells.

This case study shows the need for and value of combining mesoscale modelling and microscale modelling in order to capture the effects of the different scales in the flow modelling, and it demonstrates how the wind gradients over distance may have significant impact on resource assessments. WASA NWA can mediate the problem.

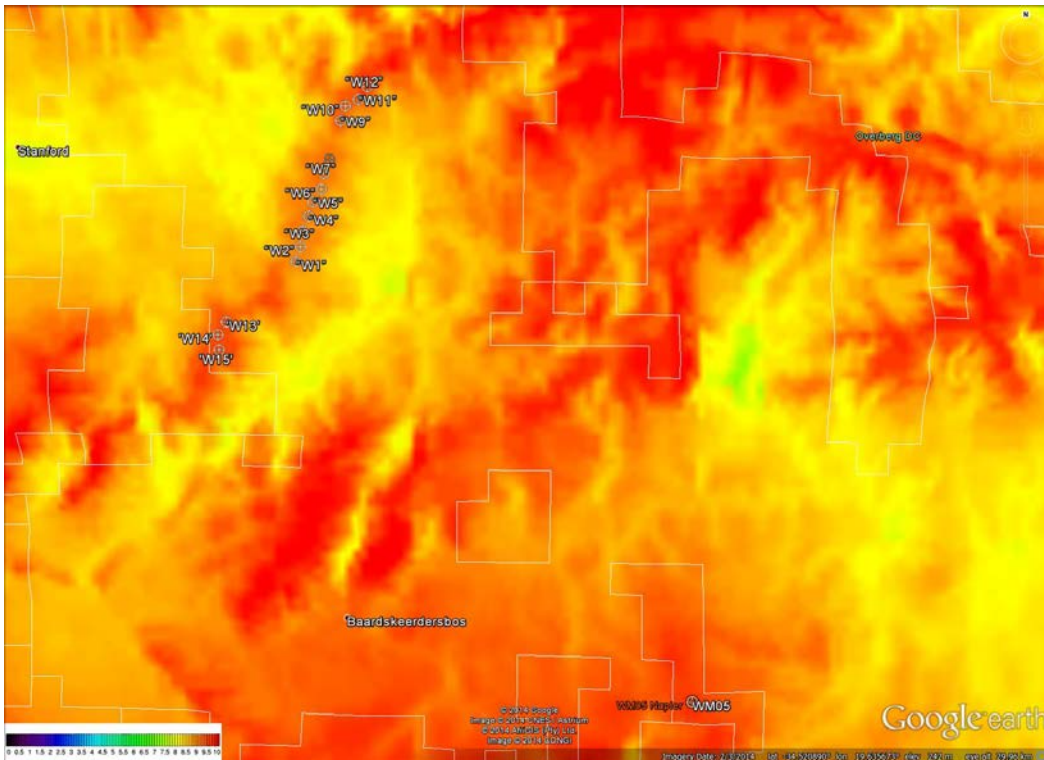


Figure 30. Case study wind farm at Stanford – plotted on WASA high-resolution wind resource map with 250 m grid spacing.

6.6 Case study – Extreme wind analysis

Wind farm development by a potential wind farm owner will also need a study of design wind conditions, for which the WASA Extreme Wind Atlas may be applied.

The site assessment that a developer needs to do in order to classify the site can include the following:

- Use data downloaded from the WASA Extreme Wind Atlas to make an initial assessment of the site wind conditions.
- From this, the class of turbine suitable for the site can be determined from the IEC standard 61400-1.
- Analysis software (e.g. WAsP Engineering) can be used to then model the extreme wind and turbulence intensity at the point of interest (in this case nearest point to the WM05 location has been analysed).
- In case of using WAsP Engineering for the study, the site information concerning terrain is the same as that used in the WAsP modelling.

Figure 31 below is a screen image showing the Generalised Extreme Wind Climate imported into WAsP Engineering.

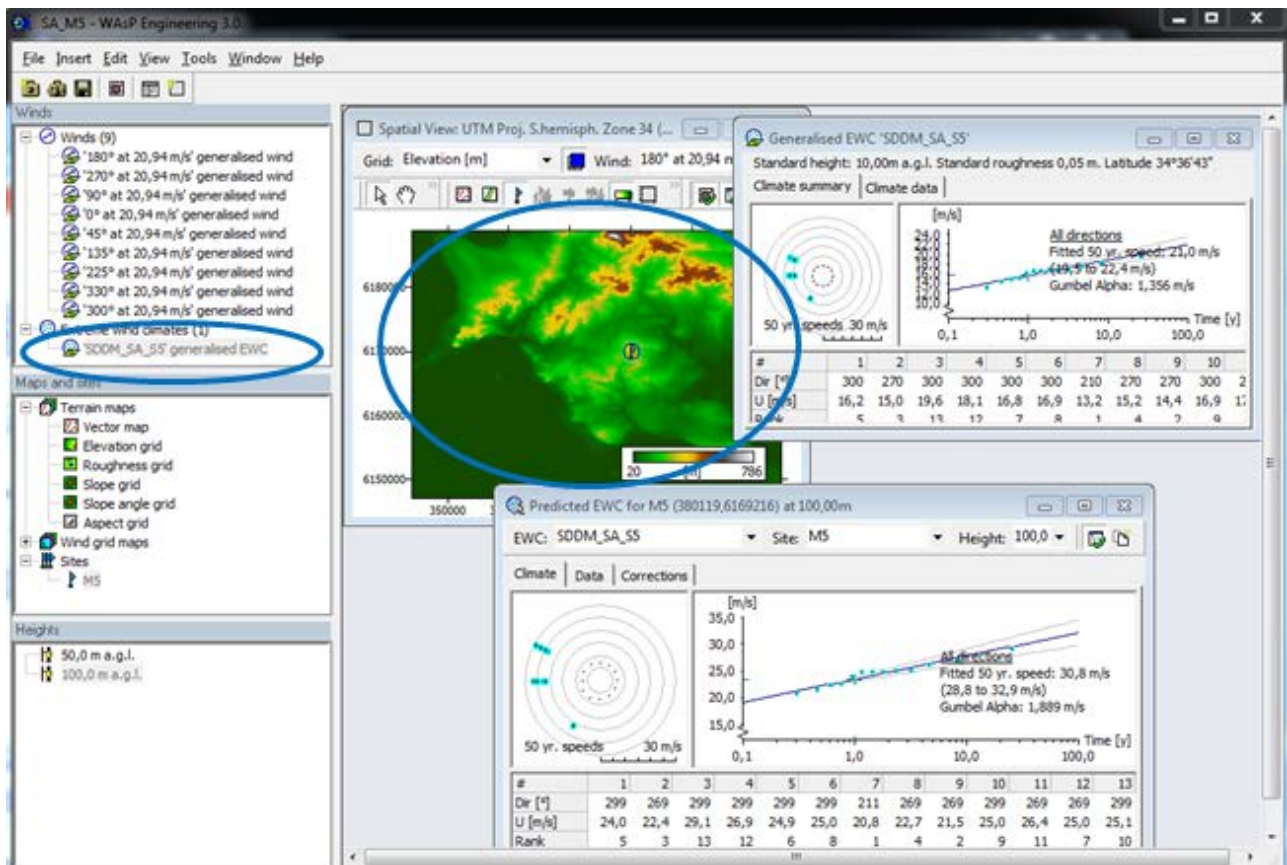


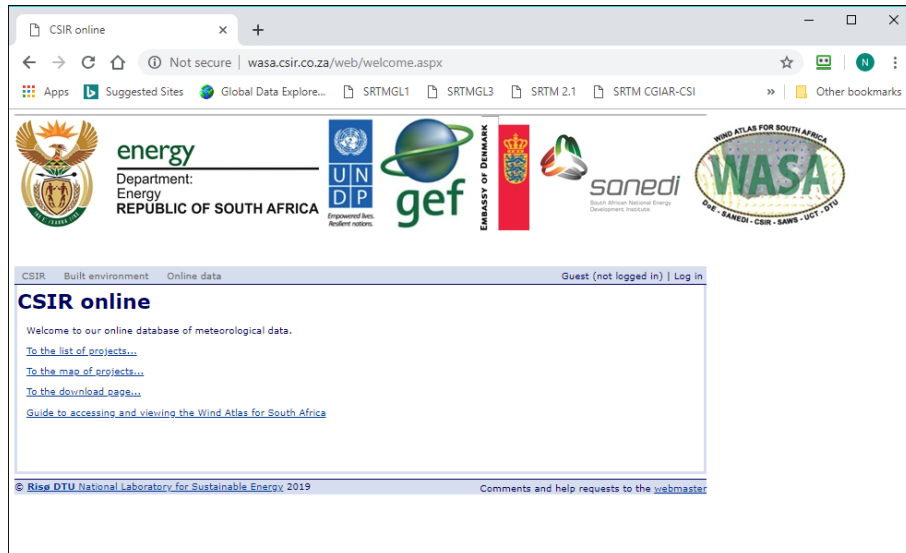
Figure 31 Generalised extreme wind climate (GEWC) file imported into WEng

This estimate of the extreme 50 year return wind speed at 100 m above ground level is 30.8 m/s.

7 Accessing and using the WASA data

There are two main project websites for data and documents:

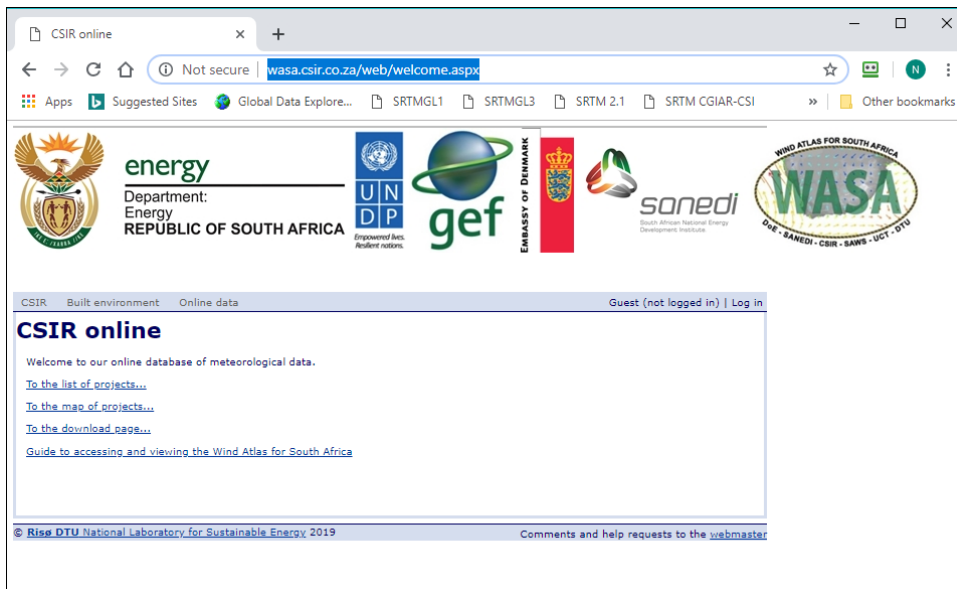
- <http://www.wasa.csir.co.za> mainly for data and guidelines



- <http://www.wasaproject.info/index.html> mostly news and information about the project



Downloading the WASA data is basically possible by following the guidance available on the websites mentioned above. In this report it is briefly illustrated by showing some screen-shots of the key steps necessary, with a few comments intended to give an overview and guidance:



- Information and links to each WASA met. mast
- Map with location and links to each WASA met. mast
- Access to data download pages
- Guide for accessing information

7.1 Access to data download pages

The screenshot shows a web browser window with the URL `wasadata.csir.co.za/wasa1/WASAData`. The page features a header with logos for the Department of Energy, Republic of South Africa, UNDP, gef, Embassy of Denmark, and SANEDI. A statistics box shows 6694 total hits and 834 unique visitors. Below the header, there are links for WASA Online Graphs, WASA FAQ, and specific data download links for WASA1, WASA2, and WASA3. A 'Message Board' section contains a list of updates regarding data availability for March 2019, February 2019, and December 2018. The main content area is titled 'Welcome to the WASA download site' and provides instructions for users who are already registered (login) or not yet registered (registration form). The registration form includes fields for first name, surname, company name, affiliation type, intended usage, address, country, telephone, email, password, and confirm password.

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Other links: [WASA Online Graphs](#) [WASA FAQ](#)
WASA1: [Arrangement Drawing](#) [Instrumentation Summary](#) [Mast Site Information](#) [Station and Site Description Report \(April 2014\).pdf](#)
WASA2: [Arrangement Drawing](#) [Instrumentation Summary](#) [Mast Site Information](#) [Station and Site Description Report \(April 2017\).pdf](#)
WASA3: [Arrangement Drawing](#) [Instrumentation Summary](#) [Mast Site Information](#)

Message Board:

- Please note: All the date/times are in SAST (UTC +2)
- 2019/04/03: March 2019 data now available. (WASA3)
- 2019/03/11: February 2019 data now available. (WASA1, WASA2 & WASA3)
- 2019/02/15: WM16 directions were 180 degrees out, and are now fixed
- 2019/02/07: January 2019 data now available. (WASA1, WASA2 & WASA3)
- 2019/01/09: December 2018 data now available. (WASA1, WASA2 & WASA3)

Welcome to the WASA download site

If you are **already registered**, and want to download data, OR if you want to **check whether you are registered**, please complete the log in form below, and press the '**Log in**' button. If you have **forgotton your password**, please fill in your e-mail address, and press the '**Send Password**' button. It will be sent to you by e-mail.

E-mail:
Password:

If you have **not yet registered**, and want to download data, please complete the registration form below.

First name: *
Surname: *
Company name / Affiliation / Personal user: *
Affiliation type: *
If 'Other' above, please enter:
Intended usage: *
If 'Other' above, please enter:
Address: *
Country: *
Telephone: *
E-mail: *
Password: *
Confirm Password: *

To download data, either

- login using your e-mail and password, or
- register if you are a first-time user -- access and use is free of charge

This page also contains links to mast specifications and site description reports.

7.2 Download of data overview

WASAData

Not secure | wasadata.csir.co.za/wasa1/WASAData

Apps Suggested Sites Global Data Explore... SRTMGL1 SRTMGL3 SRTM 2.1 SRTM CGIAR-CSI Tilpas hyperlinks

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WASA3: [Arrangement Drawing](#) [Instrumentation Summary](#) [Mast Site Information](#)

Log out

Welcome to the WASA download site, Niels G

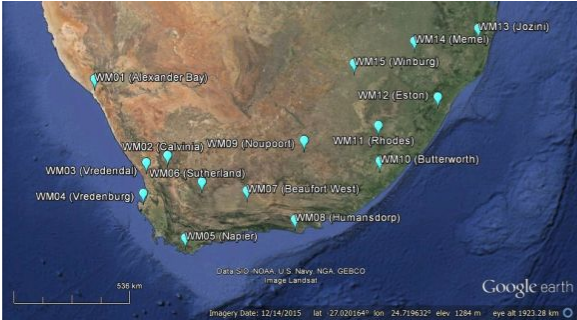
You are logged in as nimo@risoe.dtu.dk

[WASA1 Final Reports April 2014](#)
[WASA1 Wind time series downloads](#)
[WASA1 Extreme wind atlas downloads](#)
[WASA High-Resolution Wind Resource Map \(December 2018\) UPDATED \(2019/03/29\)](#)
[WASA1&2 Interim High-Resolution Wind Resource Map \(October 2017\)](#)
[WASA1 High-Resolution Wind Resource Map \(October 2017\)](#)
[WASA1 Large Scale Wind Resource Map \(April 2014\)](#)
[WASA1 Large Scale Wind Resource Map \(May 2013\)](#)
[WASA Wind Atlas downloads](#)

WASA Meteorological data downloads
Please choose the sites from which you wish to download data.

- ☐ WM01 (28°36'06.7"S, 16°39'51.9"E - since 2010-06-23)
- ☐ WM02 (31°31'29.7"S, 19°21'38.7"E - since 2010-06-30)
- ☐ WM03 (31°43'49.4"S, 18°25'10.1"E - since 2010-06-24)
- ☐ WM04 (32°50'41.2"S, 18°06'34.5"E - since 2010-05-18)
- ☐ WM05 (34°36'41.6"S, 19°41'30.3"E - since 2010-05-20)
- ☐ WM06 (32°33'24.4"S, 20°41'28.7"E - since 2010-09-17)
- ☐ WM07 (32°58'00.2"S, 22°33'23.8"E - since 2010-05-28)
- ☐ WM08 (34°06'32.0"S, 24°30'49.0"E - since 2010-08-04)
- ☐ WM09 (31°15'05.8"S, 25°01'50.2"E - since 2010-09-01)
- ☐ WM10 (32°05'26.5"S, 28°08'09.0"E - since 2010-08-05)
- ☐ WM11 (30°48'51.6"S, 28°04'25.3"E - since 2015-10-27)
- ☐ WM12 (29°51'00.4"S, 30°31'42.8"E - since 2015-10-16)
- ☐ WM13 (27°25'34.2"S, 32°09'58.1"E - since 2015-10-15)
- ☐ WM14 (27°52'54.1"S, 29°32'36.4"E - since 2015-10-02)
- ☐ WM15 (28°37'11.9"S, 27°07'23.4"E - since 2015-09-30)
- ☐ WM16 (29°26'39.2"S, 19°21'25.1"E - since 2018-10-25)
- ☐ WM17 (29°45'29.1"S, 23°31'12.6"E - since 2018-11-09)
- ☐ WM18 (27°35'50.5"S, 23°39'19.4"E - since 2018-11-08)
- ☐ WM19 (27°43'36.1"S, 20°34'06.0"E - since 2018-10-24)

Go!



Here, you can download

- High-resolution wind resource maps (several editions)
- Wind atlas data sets for all of South Africa
- Data from all 15 WASA met. masts

7.3 Wind atlas downloads page

WASAData

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Apps Suggested Sites Global Data Explore... SRTMGL1 SRTMGL3 SRTM 2.1 SRTM CGIAR-CSI Tilpas hyperlinks

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[Home / Download Data](#) [Log out](#)

The WASA download site

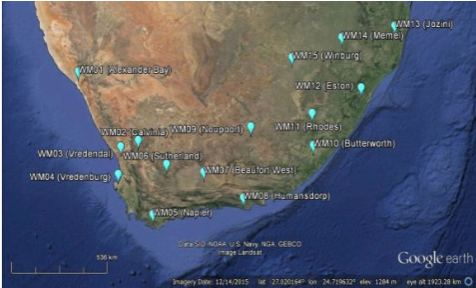
This is the download site for the **Numerical atlas for South Africa**

- [Numerical Wind Atlas](#) **UPDATED (Jun 2018)**
- [WASA Observational Wind Atlas](#) **UPDATED (Dec 2018)**
- [Case studies](#) **UPDATED (Dec 2018)**
- [Reports and Guidelines](#) **UPDATED (Dec 2018)**
- [Map data and tools](#) **UPDATED (Dec 2018)**
- [Software](#) **UPDATED (Dec 2018)**

To provide feedback to the WASA team, you can optionally download and fill in the [questionnaire](#), and e-mail to the [Webmaster](#)

Numerical Wind Atlas

The WASA numerical wind atlas contains generalized wind atlas data sets for tens of thousands of model grid points covering all of South Africa. The WASA programme has three phases. WASA1 for the domain of WC and areas of NC and EC was completed in 2014. WASA2 focus is KZN, EC and FS, while WASA3 is modelling all of South Africa. WASA2 and WASA3 are ongoing with completion in 2018 and 2020 respectively. WASA1 measurements have been continued through all phases since 2010. WASA2 measurements were added since 2015 and WASA3 measurements will be on line from mid-2018. The location of the 10 WASA1 met. stations as well as the 5 WASA2 met. stations are shown here:



The wind atlas data sets for each grid point are stored in a database; the grid point locations can be viewed in Google Earth:

[Download](#)

Here, you can download

- Numerical wind atlas data – LIB or NC files
- Observational wind atlas data – OWC and LIB files
- Case study data sets in the form of WASP workspaces
- Reports and guidelines
- Map data and tools
- Software tools

8 Concluding remarks and recommendations for applications

Wind atlas WASA databases for the entire South Africa are now made available in the public domain from a WASA web site www.wasa.csir.co.za, although any use of these databases will be fully at the users own risk. Neither of the WASA partners – SANEDI, CSIR, UCT, SAWS nor DTU – will have any liability in connection with the use of the WASA databases or the reports made by the project.

In summary, it is noted that the WASA project has produced

- Measurements and data from 2-8 years of measurement at 15 WASA stations
- 15 Observational Wind Atlases
- WRF-based Numerical Wind Atlas – updated December 2018
- High-Resolution Wind Resource Map – updated December 2018
- Extreme Wind Atlas – studies for the WASA 2 domain

All data and reports as well as guidelines for the application are available in the public domain.

The WASA project has achieved a general reduction in uncertainties – and in some cases removed uncertainties almost completely – in many aspects of wind resource assessment and assessment of wind turbine design conditions in South Africa.

This has been achieved, firstly by setting up the 15 WASA meteorological masts and recording wind data according to best practices for the validation of the Numerical Wind Atlas for South Africa; and secondly, through a thorough and systematic development of modelling methods that has included mesoscale modelling by applying the newest version of WRF applicable both regarding wind resource assessment and extreme wind statistics. The Observational Wind Atlases at the 15 WASA measurement station locations have in all locations been carefully checked and recommendations for local adaptation of WAsP model parameters have been made. The newest version of the microscale modelling tool, WAsP 12, has been applied.

The WRF-based Numerical Wind Atlas has been validated against the OWA of the 15 WASA measurement stations, WM01 – WM15.

It is recommended by the WASA project to use the newest WRF-based WASA NWA, released December 2018.

When using the WRF-based Numerical Wind Atlas and the associated High-Resolution Wind Resource Map it should, however, be noted that it is not necessarily a conservative (underestimating the resource) estimation, but in some areas (the validation shows) it seems that it may even overestimate wind speeds slightly at certain locations. Overall there is, however, good agreement between the validation measurements and the WRF-based WASA NWA, both in terms of annual average wind speeds as well as in terms of distributions and wind roses.

Various types of possible applications have been illustrated, including application for planning and application for wind farm studies.

The NWA LIB-files provide information about geographical variation of the wind climate that may have significant impact on wind resource assessment at areas with wind climate gradients – as shown in the case studies, which show potential errors that may be made if wind resource assessment is made based on measurements – even relatively close to the wind farm site studied.

It is recommended to consult the validation made for the NWA when assessing uncertainties in energy yield studies, and it is stressed not to negate the necessity for on-site measurements that will reduce uncertainties and thereby capital costs.

Some general recommendations for application of the wind atlas databases are

- Use sensitivity analyses for model parameter studies and uncertainty assessments
- Use model parameters recommended for local conditions
- Be aware of additional uncertainties not described by the present project, such as inter-annual variations and large-scale wind farm effects.
- Risk assessment of wind farm projects should look for gradients in the NWA
- Masts should remain operational as reference, which will reduce project development time and which will be useful in the further improvement of the wind atlases.
- Update the Numerical Wind Atlas every year with improved validation
- Courses in application of the Wind Atlas may be offered by CSIR and experience from the use of it in South Africa should be collected by CSIR.

Recommendations for measurements are

- Follow international standards for high-quality measurements
- Use top-anemometer as a reference
- Minimize flow distortion effects from booms, masts, etc.
- Use highest instrument quality and calibrations in traceable wind tunnels
- Use data acquisition system with redundancy to get >95% data recovery

Recommendations for microscale modelling are

- Apply WAsP correctly in order to obtain correct performance as was found by the sensitivity studies at the 15 masts in South Africa.
- Use recommended parameters for WAsP in South Africa
- Use WAsP CFD in complex terrain, with RIX numbers higher than just a few percent, and compare also to WAsP IBZ. Modelling results in complex terrain should be treated carefully.
- Ensure high accuracy of wind and topographic data to achieve low uncertainties
- Use of *.LIB files from NWA recommended
- A check list of requirements, best practices and recommendations for microscale modelling is annexed in A. The list is not exhaustive, but is meant to provide a brief summary of some important considerations regarding microscale modelling of general importance when applying the Numerical Wind Atlas or making Observational Wind Atlas from the measurements of this project or from any other measurements in South Africa.

It should be remembered that at certain locations only 2 or 3 years of measurement data is used for the model validation. When the validation period is shortened one normally expect an increase in the uncertainty, therefore further measurements at current sites and additional sites would be of great value for validation. Multi-year measurements would allow for an assessment of uncertainty for single year mean wind statistics.

All in all, one may conclude that the WRF-based numerical wind atlas in combination with observational wind atlases offer new opportunities for doing wind farm planning on a large scale, even with a limited availability of wind data from meteorological measurement stations. At wind farm sites and in project preparation it provides a consistent basis for validation of model results against each other and against measurements when employing the wind atlas method and together it may be applied with a view to

reducing uncertainties. Evidently techniques may be improved through a continued research effort making use of the ever increasing computing power of new computers and new measurement technologies like LIDARS to measure higher above ground level, mapping techniques and maybe even satellite imagery.

9 References

- Badger, J., H. Frank, A. N. Hahmann, and G. Giebel, 2014: Wind-climate estimation based on mesoscale and microscale modeling: Statistical-dynamical downscaling for wind energy applications. *Journal of Applied Meteorology and Climatology*, 53, 1901–1919.
URL <http://journals.ametsoc.org/doi/abs/10.1175/JAMC-D-13-0147.1>
- Bowen, A. J., & Mortensen, N. G. (1996). Exploring the limits of WAsP the wind atlas analysis and application program. In A. Zervos, H. Ehmann, & P. Helm (Eds.), 1996 European Union wind energy conference. Proceedings (pp. 584-587). Bedford: H.S. Stephens & Associates.
- ECMWF, 2016: ERA5 reanalysis is in production.
URL <http://www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production>.
- Frey-Buess, F., D. Heimann, R. Sausen, 1995. A statistical-dynamical downscaling procedure for global climate simulations. *Theor. Appl. Climatol.*, 50:117-131
- Hahmann, A. N., C. L. Vincent, A. Peña, J. Lange, and C. B. Hasager, 2015c: Wind climate estimation using WRF model output: Method and model sensitivities over the sea. *International Journal of Climatology*, 35, 3422–3439.
- Hansen, J.C., N.G. Mortensen, J. Badger, N.-E. Clausen and P. Hummelshøj (2007). Opportunities for wind resource assessment using both numerical and observational wind atlases – modelling, verification and application. In Proceedings of *Wind Power Shanghai 2007*, Shanghai (CN), 1-3 Nov 2007. (Chinese Renewable Energy Industry Association, Shanghai, 2007) p. 320-330.
- Hansen, J.C., N.G. Mortensen, T. Cronin, M. Nielsen, A. Hahmann, J. Badger, X. Larsén, E. Mabilie and E. Prinsloo (2014). Best practice guide for application of WASA. Department of Wind Energy, Technical University of Denmark (DTU) and Council for Scientific and Industrial Research (CSIR). April 2014, 56 pp
- IEC 61400-12-1. Wind turbines-Part 12-1: Power performance measurements of electricity producing wind turbines, 2005. IEC 2009
- Mortensen, N.G., J.C. Hansen, J. Badger, B.H. Jørgensen, C.B. Hasager, L. Georgy Youssef, U. Said Said, A. Abd El-Salam Moussa, M. Akmal Mahmoud, A. El Sayed Yousef, A. Mahmoud Awad, M. Abd-El Raheem Ahmed, M. A.M. Sayed, M. Hussein Korany, M. Abd-El Baky Tarad (2005). Wind Atlas for Egypt, Measurements and Modelling 1991-2005. New and Renewable Energy Authority, Egyptian Meteorological Authority and Risø National Laboratory. ISBN 87-550-3493-4. 258 pp.
- Mortensen, N.G., D.N. Heathfield, L. Myllerup, L. Landberg and O. Rathmann (2007). Wind Atlas Analysis and Application Program: WAsP 9 Help Facility. Risø National Laboratory, Technical University of Denmark, Roskilde, Denmark. 353 topics. ISBN 978-87-550-3607-9.
- Mortensen, N.G., J.C. Hansen, M.C. Kelly, S. Szewczuk, E. Mabilie and E. Prinsloo (2014). Wind Atlas for South Africa (WASA) – Observational wind atlas for 10 met. stations in Northern, Western and Eastern Cape provinces. Department of Wind Energy, Technical University of Denmark (DTU) and Council for Scientific and Industrial Research (CSIR). April 2014, 63 pp.
- Mortensen, N. G., Yang, Z., Hansen, J. C., Rathmann, O., & Kelly, M. C. (2010). Meso- and Micro-scale Modelling in China: Wind atlas analysis for 12 meteorological stations in NE China (Dongbei). Risø National Laboratory for Sustainable Energy, Technical University of Denmark. Risø-I, No. 3072(EN)
- Troen, I. and E.L. Petersen (1989). *European Wind Atlas*. ISBN 87-550-1482-8. Risø National Laboratory, Roskilde. 656 pp.

A. List of requirements, best practices and recommendations

The following list of requirements, best practices and recommendations is not exhaustive, but is meant to provide a brief summary of some important considerations regarding WAsP modelling. More information is available in the WAsP help system and at www.wasp.dk.

Measurement programme

- Design measurement programme based on preliminary WAsP analysis
 - Use SRTM elevation data and land-use from Google Earth
- Follow similarity principle as much as possible when siting the mast(s)
- Height of reference anemometer(s) similar to hub height (preferably $> 2/3 h_{\text{hub}}$)
- Optimum boom direction is @ 90° (lattice) or @ 45° (tubular) to prevailing wind
- Deploy 2 or more masts for horizontal extrapolation analyses
- Deploy 2 or more masts if RIX and Δ RIX analyses are required
- Deploy 2 or more levels on masts for vertical wind profile analyses
- Deploy 2 or more levels on masts for redundancy in instrumentation
- Measure temperature and pressure for air density calculations

Wind data analysis

- Collect required information, e.g. by filling out the WAsP Data Description Form
- All fields in Climate Analyst protocol editor should correspond to data spec's
- Plot and inspect time traces of all meteorological measurements
- Visual inspection of time-series – in particular reference wind speed and direction
- Visual inspection of polar scatter plot – any patterns or gaps?

Observed wind climate

- Use an integer number of whole years when calculating the OWC
- Check Weibull fit: is mean wind power density discrepancy $< 1\%$?
- Check Weibull fit: is mean wind speed discrepancy $< \text{a few per cent}$?
- Check within context of long-term wind climate (MCP)

Elevation map(s)

- Size of map: should extend at least $\max(100 \times h, 10 \text{ km})$ from any site – meteorological mast, reference site, turbine site or resource grid point.
- Coordinates and elevations must be in meters
- Set projection and datum for map in the Map Editor
- Add spot heights within wind farm site
- Check range of elevations in map

Roughness/Land-use map(s)

- Size: map should extend at least $\max(100 \times h, 10 \text{ km})$ from any site – meteorological mast, reference site, turbine site or resource grid point.
- Coordinates and elevations must be in meters
- Set projection and datum for map in the Map Editor
- Set roughness length of water surfaces to 0.0 m!
- Check range of roughness values in map
- Map date should correspond to modelling scenario (met. mast or wind farm)
- Check for dead ends and cross points – and edit map as needed
- Check consistency of roughness values – there must be no LFR-errors!

Sheltering obstacles

- Is site closer to obstacle than 50 obstacle heights, and is height lower than about 3 obstacle heights?
- If yes to both, treat as sheltering obstacle; if no, then treat as *roughness element*

WAsP modelling – site visit

- Go on a site visit! Use e.g. the WAsP Site/Station Inspection Checklist
- Print and bring the WAsP forms for recording the necessary information
- Bring GPS and note projection and datum settings – change if required
- Determine coordinates of all masts, landmarks and other characteristic points on site
- Take photos of station and surroundings (12 × 30°-sector panorama)
- Download GPS data and photographs to PC as soon as possible (daily)

WAsP modelling – parameters

- Wind atlas structure: standard roughness classes should span site conditions
- Wind atlas structure: standard heights should represent project
- Adjust off- & on-shore mean- and RMS-heat flux values to site conditions (*caution*)

WAsP modelling – analysis and application

- Get site-specific wind turbine generator data from manufacturer
- Within forest: effective height = nominal height minus displacement length
- Complex or steep terrain is when $RIX > 0$ for one or more sites (terrain angles $> 17^\circ$)
- Make RIX and ΔRIX analyses if $RIX > 0$ for any site

WAsP modelling – offshore

- Roughness length of sea (and other water) surfaces: set = 0.0 m in WAsP!
- Add combined elevation/roughness change line around wind farm site
- Change wake decay constant to offshore conditions

WAsP modelling and sensitivity analyses

- Identify and try to estimate uncertainties
- Sensitivity of results to background roughness value and other important parameters

DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 230 staff members of which approximately 40 are PhD students. Research is conducted within ten research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

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